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THERMIONIC TOPPING CONVERTER FOR A COAL-FIRED POWER PLANT

Anthony J. Cassano, et al

Consolidated Controls Corporation
Bethel, Connecticut

1970

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UNITED STATES

DEPARTMENT OF THE INTERIOR

OFFICE OF COAL RESEARCH
RESEARCH AND DEVELOPMENT REPORT NO.

THERMIONIC TOPPING CONVERTER FOR A COAL-FIRED POWER PLANT

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Prepared for

OFFICE OF COAL RESEARCH
DEPARTMENT OF THE INTERIOR
WASHINGTON, D.C. 20240

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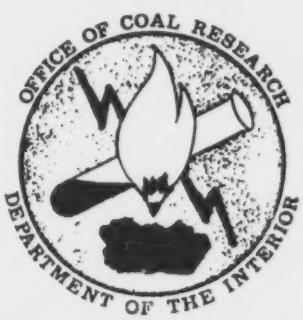

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Final Report

THERMIONIC TOPPING CONVERTER FOR A COAL-FIRED POWER PLANT

Prepared for:

OFFICE OF COAL RESEARCH
DEPARTMENT OF THE INTERIOR
WASHINGTON, D.C. 20240

CONTRACT 14-01-0001-499

By: ANTHONY J. CASSANO
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CCC Project 60-6445

CCC Report 60-6445-17

Approved: RICHARD E. ENGDAHL, MANAGER
Advanced Research and Development

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FOREWORD

This is the final technical report under Contract 14-01-001-499, conducted by Consolidated Controls Corporation, under sponsorship by the Office of Coal Research, U. S. Department of the Interior. Mr. G. I. Staber, Assistant Chief of the Utilization Division, was project monitor for the Office of Coal Research.

Project supervision was by R. E. Engdahl, Manager of Advanced Research and Development. Principal investigators were A. J. Cassano, Research Physicist and J. R. Bedell, Techniques Manager.

Information on present practices, and costs of conventional equipment in the areas of fuel burning and steam generation were supplied by Combustion Engineering, Inc., under one phase of a sub-contract, which also included a program to test thermionic diodes in a laboratory coal-fired furnace. In addition, we would like to acknowledge the help of G. Palo of T.V.A. for providing the Bull Run information used in the analysis. M. K. Burk and L. M. Harvey of General Electric Company have been of great help in supplying the characteristics and analysis of the acyclic motor system.

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1.0 INTRODUCTION

The generation of electrical power by all predictions will about double every 10 years for the forseeable future. Considering that the U. S. electrical utility industry is presently using fuel at the rate of 1.5×10^{16} Btu/year, careful consideration must be given to methods which will result in maximum use of our coal resources. Coal presently provides more than 50 percent of the fuel used by electric utilities and about 25 percent of the total national fuel requirements.

This fuel management effort is important to assure that we will have available fuel for future electrical power and also that we will minimize the dissipation of waste heat and other pollution products that can prove to be detrimental to man's environment.

The Division of Utilization of the Office of Coal Research is committed to persue these goals through improved use of our coal reserves. As part of this effort, Consolidated Controls Corporation has been working on a program leading to the design, construction and test of thermionic energy converters capable of acting as a turbine-topping system in a coal-fired central power station.

Combining the thermionic topping system with a conventional steam cycle promises a substantial increase in plant output and efficiency, as well as a decrease in thermal and atmospheric pollution in relation to power generated. In addition to these improvements in performance, it is estimated that a significant reduction in capital and fuel costs will result from the use of thermionic topping.

The research conducted at CCC under OCR sponsorship (Contract 14-01-0001-499) involved two basic areas, including:

1. The preparation of a performance and cost comparison study between a coal-fired central station without thermionic topping and one with thermionic topping, and

2. The design, construction and testing of thermionic converters. The test program included operation in a coal-fired environment.

This report covers the work performed under this contract.

In addition to this report, the following technical papers were prepared based on the work performed under this contract. The papers were prepared for presentation to a relatively wide cross-section of technical audience.

"Thermionic Topping - The Key to Coal Fired Central Power Station Efficiency" - American Power Conference. April 1968.

"Thermionic Energy Conversion for Central Power Stations" Intersociety Energy Conversion Engineering Conference, August 1968.

"Thermionics in Fossil - Fuel and Nuclear Central Power Stations" - IEEE Winter Power Meeting, January 1969.

2.0 SUMMARY

We have conducted a two-phase investigation into the feasibility and practicality of thermionic topping as applied to a coal-fired central power station. The work included a comparison analysis of a modern station to indicate the inherent advantages of thermionic topping and an experimental and materials effort to establish the guide lines for fabrication of the thermionic converters and selection of materials specifically required by the thermionic plant.

The results of this program indicate that thermionic topping is an attractive system concept which can significantly improve the operation of a central station without any great effect on the basic design of the station and its equipment. In this way, it appears possible to draw upon the extensive operating experience and reliability of the modern plant while significantly improving the station efficiency and cost structure.

The comparison study was performed on the T.V.A. Bull Run plant and showed that thermionic topping would improve the station performance from 914 megawatts output at 41.3 percent efficiency to 1,139 megawatts at 50.6 percent, while lowering the electrical generating capital costs from $156 to $141 per kilowatt and affecting an annual fuel cost saving of up to $2.7 million.

The basic design changes involve the modification of the present-day boiler to include the installation of thermionic diode modules whose electrical output is delivered to a high-efficiency acyclic motor, which in turn drives one of the station generators in tandem with the low-pressure turbine. Thus the thermionic output is integrated into the station output by one piece of station equipment; the acyclic motor. The only other piece of station equipment peculiar to the topped plant is a final air heater, used to extract heat from the exhaust gas and raise the temperature of the secondary (combustion) air to about 2300°F. Our studies indicate that this heat exchanger is quite feasible both in design and materials and is readily incorporated into the thermionic furnace module.

Aside from these modifications, the basic design of the central station remained intact.

The second part of the overall program involved the design, construction and test of thermionic converters and the demonstration of a materials capability in two areas: As a protective envelope for the thermionic converter against the combustion gas environment and as the heat exchange medium for the final air heater mentioned above.

A total of 18 thermionic converters were tested with power output levels of up to 133 watts (design output of 100 watts) and operating lifetimes of up to 318 hours. Two of these converters were operated in a coal-fired environment; one of them for 127 hours (85 hours in coal-fired environment) at 112 watts output. While our testing showed no serious problem with the hot, slagging end of the converter, our design work concentrated on the cold end, where failures were concentrated. Recent work has progressed to the point where the solution to this problem appears to be near.

Slagging tests run on silicon carbide ceramic material for the final air heater were successful, indicating the suitability of the ceramic as the heat exchange material.

In summary, the program indicated both the feasibility and the practicality of thermionic topping in a central station. What is ahead of us is the demonstration of a viable multiple-diode thermionic module design and the fabrication and test of a small scale coal-fired test system. It appears that the attractiveness of thermionic topping makes these near-term goals well worth attaining.

3.0 POWER PLANT COMPARISON STUDY

One part of our work on this program involved a performance and cost comparison study between a coal-fired central station without thermionics and one with thermionics. In this way, some idea could be obtained of the practical aspects of thermionic topping. To be useful, thermionic topping must improve the station performance, but must do so without adversely affecting the station cost structure.

The comparison study was performed on a modern central station, the T.V.A. Bull Run plant, operating with a supercritical steam cycle. The study indicated that thermionic topping would increase the station output and efficiency from 914 megawatts at 41.3 percent to 1,139 megawatts at 50.6 percent. In addition, thermionic topping is estimated to result in lower electrical generating capital costs, $141 per kilowatt as opposed to $156 per kilowatt without topping, and an annual fuel cost saving of up to $2.7 million.

Clearly, thermionic topping for central power stations holds promise for improving the efficiency and reducing the capital equipment costs.

3.1 THERMIONIC TOPPING

Thermionic energy conversion is a technique for converting heat directly into electricity. The basic thermionic configuration consists of a refractory metal emit spaced about 0.010 inch from a collector. The applied heat is delivered to the emitter, whose temperature is raised to about 2750°F. Electrons are "boiled off" the emitter, cross the interelectrode gap, and enter the collector with sufficient excess energy to deliver power to an external load. The space charge potential, inherent in the interelectrode space, is neutralized by low pressure cesium vapor which ionizes to form a conductive plasma. The efficiency limitation of any power cycle depends on the source and sink temperature. Since the sink temperature is fixed by the surroundings, design improvements are usually directed at increasing the allowable source temperature. The essential feature of thermionic topping is that it extracts energy from the fuel at a temperature considerably higher than is currently practiced. This increases the availability of the energy. As stated above, emitter temperatures range about 2750°F. In addition, the collector temperature of a thermionic converter (about 1200°F) is ideally suited to raise steam used in conventional superheat and reheat systems.

An analysis of the general thermionic topping system brings one fact into sharp focus. To obtain maximum plant efficiency, it is necessary to maximize the amount of heat in the combustion gases that pass through the thermionic converters. To accomplish this, an additional air heater is added and the superheat and reheat functions are incorporated into the thermionic collector surfaces. As stated above, the emitter and collector temperatures are ideally suited for these functions.

In addition to modifications in boiler design, a critical appraisal of the combustion air system must be made. Extremely hot gas must be delivered to the thermionic converters. Experiments carried out in our laboratories over the past several years indicate that the thermionic converters should be exposed to gases at about 3100°F in order to establish proper operating conditions in the converters. Further, our tests have shown that the secondary air should be preheated to about 2300°F to obtain the necessary combustion gas temperature. While these hot gases can be generated without difficulty by using pulverized coal and secondary air preheated to about 2300°F, the final air heater represents another departure from

existing technology. It should be emphasized that the role of the final air heater is to raise the secondary air temperature as high as possible so that the maximum amount of fuel heat is delivered to the thermionic diode modules, rather than being delivered to the secondary air. Both design areas, the thermionic furnace and the final air heater, will be discussed in detail in later sections of this report. Suffice it to say here that both areas are unique to thermionic topping plants.

A wealth of theoretical and experimental data on thermionic converter devices has been accumulated over the past ten years. Based on the temperature parameters of this study, a thermionic conversion efficiency of 15 percent appears to be a reasonable assumption. This means that of the total combustion gas heat delivered to the thermionic converters, 15 percent is converted directly to electrical power and 85 percent is delivered to the collectors. This heat is then transferred to the superheat and reheat steam piping.

Consider a thermionic module which uses heat at 2750°F and is cooled by steam at temperatures and pressures customary to modern central stations. A thermionic topping system is a group of these modules combined in such a way that their electrical output increases the electrical output of a power station and heat rejected from the modules provides the heat input to the steam portion of the power station. Figure 1 shows a diagram of the energy flow through such a system. Since the steam cycle is not changed, the output of the thermionic topping system represents the increase in useful work. From the efficiency standpoint, it is desireable that all the input energy pass through the thermionic system to the steam system. Since this is not possible in practice, an economizer must be provided to absorb the energy that bypasses the thermionics. In this manner it is possible to devise an arrangement where the only energy rejected is the familiar condenser and stack losses.

The efficiency of a thermionic device increases with emitter temperature. Materials are the limiting factor. At these temperatures, however, high pressures are not encountered since thermionic devices operate at almost full vacuum. Thus, the failure hazards of a high-temperature, high-pressure system are eliminated. In addition, for the steam portion of the cycle, the corrosion problems are reduced since the heat transfer surfaces are not exposed to the high temperature flue gases.

In practice, the general topping system would take the form of Figure 2. Pulverized coal, along with air preheated to about 2300°F, are introduced and combusted in a thermionic furnace. The combustion gases are passed over the thermionic converters, raising the emitter temperature to about 2750°F, and exit the furnace at a temperature about 3100°F. Exhaust gas heat is recovered in three heat exchangers; a final air heater designed specifically for high temperature operation, a conventional rotary air preheater, and an intermediate economizer which delivers steam above the critical point. The exhaust gases leave the plant at about 300°F. The steam generated in the economizer is superheated to 1000°F, by passing through the thermionic converters and accepting the heat available at the collector surfaces. Assuming a 15 percent converter efficiency, 85 percent of the heat passing through the converters is thus delivered to the superheat and reheat systems. The superheated steam is expanded through a high-pressure turbine, reheated from 550°F to 1000°F by another pass through the thermionic converters, and then expanded through the intermediate and low-pressure turbines. Aside from superheat and reheat, the steam is treated as it would be in any conventional power station (condenser, low-pressure and high-pressure feedwater heaters, deaerator, and condenser polishing where advisable). Thermionic electrical energy is delivered directly to the electrical system and the steam power is delivered by conventional means.

Figures 3 and 4 present, in schematic form, a comparison of a coal-fired central power station without and with thermionic topping. It can be seen that physically implementing the topping system involves the replacement of the conventional boiler by a furnace containing the thermionic converters and the addition of a power conditioning device. The regenerative heat exchangers and the economizer have not been shown but have been included as part of the boiler (Figure 3) and furnace (Figure 4).

The D.C. electrical output of the thermionic converters, which represents about 20 percent of the total electricity generated in the plant, may be conditioned in a number of ways. The most promising appears to be the use of a D.C. acyclic motor coupled to one of the turbogenerator shafts. In this way, the D.C. output is incorporated directly into the turbogenerator output and the station electrical distribution system (transformers, breakers, switchgear, controls, etc.) is identical to the systems presently in use.

The quantitative results of applying these concepts to a modern central power station, the T.V.A. Bull Run plant, are presented in Sections 3.3, 3.4 and 3.5 of this report.

3.2 SELECTION OF CYCLE

Over the past twenty years, improvements in central power station efficiency may be directly attributed to refinements in steam generator design as reflected in improved steam conditions and higher steaming rates. Figure 5 indicates the steady decline in heat rate as station capacity increases. However, the chart does not tell the whole story. Along with increased capacity, the marked improvement in heat rate is a direct result of increases in maximum steam pressure and temperature

Steam pressure has been steadily increased from the 2200 - 2400 psi maximum of the 1940's to the present supercritical level of about 3500 psi. As a rule of thumb, doubling drum pressure results in about 7 percent gain in heat rate. This gain would continue until the additional power needed for feed pumps counteracts the improvement in efficiency.

Maximum steam temperatures have risen from about 900°F to present levels of about 1000°F. Higher temperatures are possible, but demand use of austenitic steels, an approach that has been shown to be overly expensive. In all, the net heat rate has improved by about 3.5 percent as the main steam and reheat temperatures have risen from 900 to 1000°F.

Multiple reheat systems have proven to be of only slight benefit since any improvement in cycle efficiency is usually more than offset by the cost of extra steam piping and heating surface.

A further consideration exists in a possible heat balance problem inherent in stations using the subcritical steam cycle. Preliminary calculations have shown that in subcritical stations, the heat available in the exhaust gases is more than enough to raise the feedwater to the saturation temperature but not enough to provide all the heat of evaporation. The necessary remaining part of the heat of evaporation must be supplied by the heat available at the thermionic converter collector surfaces. In all likelihood, this would involve boiling in horizontal tubes. A much better solution would be the use of a supercritical system with the economizer raising the feedwater beyond the critical point and using the thermionic converters for superheat and reheat. Thus, only single phase flow will exist in the heat transfer elements with horizontal tubing.

From the above comments and our desire to apply the analysis to a modern, efficient station, it appeared that we should address the thermionic topping system to a large (about 1000 megawatts) power plant operating on a super-critical steam cycle with one reheat. Furthermore, the topping analysis requires access to relatively complete cycle performance and cost data. Obtaining such data appeared to be more feasible for a government owned plant than from a private utility.

Consideration of all the previous comments led us to select the T.V.A. Bull Run station as the one to which we will apply the thermionic topping study. A complete run-down of the Bull Run operational parameters, both with and without thermionic topping, is contained in Sections 3.3 thru 3.5. The comparative economic analyses are presented in Section 3.12.

3.3 T.V.A. BULL RUN

In Section 3.2, the factors determining the selection of a modern, efficient central power station, to which a thermionic topping analysis could be applied, were presented and discussed. Based on these factors, the T.V.A. Bull Run plant was chosen. We shall study the detailed operating steam cycle parameters as they now exist, and the variations that would be introduced into these parameters by thermionic topping. The sizable improvement in plant operation will be self-evident.

3.4 PERFORMANCE WITHOUT TOPPING

T.V.A. Bull Run is a large (914 megawatts) power plant operating on a supercritical steam cycle with one reheat. Superheated steam leaves the boiler, is expanded through a high-pressure turbine, reheated by another pass through the boiler, and then expanded through the intermediate and low pressure turbines. Two generators are used; one driven by the high and intermediate pressure turbines and the other driven by the low pressure turbine. The outputs of the generators are approximately equal.

Table 1 presents the steady state, maximum continuous load design conditions for Bull Run Unit 1. Figure 6 is the heat balance diagram, and Figure 7 shows the cycle represented on a standard temperature-entropy chart.

From the data of Table 1, further Bull Run parameters may be calculated.

$$\text{lb coal/lb. steam} = \frac{633{,}000}{6{,}334{,}200} = 0.0999$$

$$\text{lb air/lb coal} = \frac{7{,}490{,}000}{633{,}000} = 11.83$$

If primary (coal-carrying) air = 1 lb/lb coal,

Secondary (combustion) air = 10.83 lb/lb coal.

Exhaust gas flow rate = coal rate + air flow rate
= 8,123,000 lb/hr

$$\text{lb exhaust gas/lb coal} = \frac{8{,}123{,}000}{633{,}000} = 12.83$$

$$\text{Plant heat rate} = \frac{\text{BTU/hr thermal input}}{\text{kw electrical output}}$$

$$= \frac{(11{,}910 \text{ BTU/lb coal})\ (633{,}000 \text{ lb coal/hr})}{913{,}832 \text{ kw}}$$

$$= 8250 \text{ BTU/kw hr}$$

$$\text{Plant efficiency} = \frac{\text{Electrical output}}{\text{Thermal input}}$$

$$= \frac{(913{,}832 \text{ kw})\ (3414 \text{ BTU/kw hr})}{(11{,}910 \text{ BTU/lb coal})\ (633{,}000 \text{ lb coal/hr})}$$

$$= 41.3 \text{ percent.}$$

TABLE 1

BULL RUN UNIT 1 STEADY STATE, MAXIMUM
CONTINUOUS LOAD DESIGN CONDITIONS

Heat value of coal, BTU/lb	11,910
Coal rate, lb/hr	633,000
Air flow rate, lb/hr	7,490,000
Steam flow rates, lb/hr	
a. High pressure	6,334,200
b. Reheat	4,484,400
c. No. 1 bleed	1,446,800
No. 2 bleed	378,700
No. 3 bleed	351,200
No. 4 bleed	112,100
No. 5 bleed	341,700
No. 6 bleed	253,200
No. 7 bleed	130,600
No. 8 bleed	180,600
Feedwater P (psig)/T (F), boiler inlet	4100/550.9
Economizer Temp. in/out, F, gas	NA/656
Economizer Temp. in/out, F, water/steam	550.9/NA
Max. P (psia)/T (F) into HP turbine	3515/1000
Max. P (psia)/T (F) out of HP turbine	600/551.7
Max. P (psia)/T (F) into reheater	600/551.7
Max. P (psia)/T (F) out of reheater	540/1000
Air inlet temperature, F	110
Exhaust gas temperature out, F	280
Power output, kw	913,832

We shall now introduce the thermionic topping system into the analysis and obtain the resultant changes in the operational parameters.

3.5 PERFORMANCE WITH TOPPING

Changes in the Bull Run steam cycle due to thermionic topping arise from two basic considerations.

1. Secondary air is to be pre-heated to 2300°F.

2, Superheat and reheat functions, with dry steam, are to be performed by the thermionic converters.

The heat needed to raise the secondary air to 2300°F will be extracted completely from the exhaust gases. However, there will be considerable excess heat available in the exhaust gases. This excess heat will be used to perform the economizer function. The feedwater will be raised beyond the critical point to a dry steam condition determined by the excess heat in the exhaust gases. From that point, superheat and reheat become thermionic converter functions. Basically, this approach introduces a fixed intermediate point in the cycle diagram between conditions 6 and 1 (see Figure 7).

Figure 8 presents the thermionic topping cycle on a standard temperature-entropy chart. The steam conditions at point 7 along with any other changes in Bull Run parameters may be determined by the following analysis.

The cycle heat balance requires that Q_i, the thermal energy released by coal combustion be distributed among the various energy sinks, including

1) Q_s, the energy to heat the secondary air to 3100°F.

2) Q_p, the energy to heat the primary air to 3100°F.

3) Q_c, the energy to heat the coal to 3100°F.

4) Q_o, the energy delivered to steam at the collector surfaces of the thermionic converters (during superheat and reheat) and,

5) Q_T, the energy delivered by the thermionic converters as electrical output (during superheat and reheat).

If the heat balance is normalized on the basis of 1 lb of steam, and making use of the cycle paramenters presented in Section 3.4.

$$Q_i = 11{,}910A$$

$$Q_s = 10.83\ A\ Cps\ \Delta T_S$$

$$Q_p = 1.0\ A\ Cpp\ \Delta T_p$$

$$Q_c = A\ Cpc\ \Delta T_c$$

$$Q_o = (H_1 - H_7) + \frac{4{,}478{,}400}{6{,}334{,}200} \quad (H_3 - H_2)$$

$$Q_T = \frac{0.15}{0.85} \quad (H_1 - H_7) + \frac{0.15}{0.85} \quad \frac{(4{,}478{,}400)}{(6{,}334{,}200)} \quad (H_3 - H_2)$$

where all Q values are in BTU/lb steam and

A = lb coal/lb steam

Cps = specific heat of secondary air over temperature range ΔT_s = (3100 - 2300) °F. (0.289 BTU/lb °F)

Cpp = specific heat of primary air over temperature range ΔT_p = (3100-110)°F. (0.267 BTU/lb °F).

Cpc = specific heat of coal over temperature range ΔT_c = (3100-110)°F. (0.24 BTU/lb °F).

H = enthalpy at conditions during steam cycle, BTU/lb. steam.

H_1 = 1424 BTU/lb, H_2 = 1256.7 BTU/lb, H_3 = 1518.6 BTU/lb.

Substituting the appropriate values and setting

$Q_i = Q_s + Q_p + Q_c + Q_o + Q_T$ yields.

$$11{,}910A = 2504A + 798A + 718A + \frac{(1424 - H_7)}{0.85} + 185 + 33 \text{ or}$$

$$6707A + H_7 = 1609$$

The second equation to be developed involves the exhaust gas heat balance. Heat removed from the exhaust gas, Qg, is used to perform the economizer function, Qe, and to provide air pre-heat, Qa. On a per-pound-of-steam basis, these three heat terms are

$Qg = 12.8A\ Cpe\ \Delta Te$

$Qe = H_7 - H_6$

$Qa = 10.8A\ Cpa\ \Delta Ta$

Where all Q values are in BTU/lb. steam and

Cpe = specific heat of exhaust gases over temperature range Δ Te = (3100-280)°F. (0.28 BTU/lb °F)

Cpa = specific heat of secondary air over temperature range Δ Ta = (2300-110)°F. (0.27 BTU/lb°F)

Substituting the appropriate values and setting

$Qg = Qe + Qa$ yields

$10{,}100A = H_7 - 546.3 + 6400A$ or

$3700A - H_7 = -546.3$

Collecting the two heat balance equations

$6707A + H_7 = 1609$ and

$3700A - H_7 = -546.3$

yields the following values.

$A = 0.102$ lb. coal/lb steam

$H_7 = 925$ BTU/lb steam

The output delivered by the thermionic converters is

$$Q_T = \frac{.15}{.85} (1424-925) + 33 = 121 \text{ BTU/lb steam}$$

or 225,000 kilowatts, based on a steam flow of 6,334,200 lb/hour.

The total plant output is

Steam plant output	913,832 KW
Thermionic output	225,000 KW
Total	1,138,832 KW

The plant efficiency may now be calculated.

Thermal Input

$$0.102 \frac{\text{lb coal}}{\text{lb steam}} \left(11{,}910 \frac{\text{BTU}}{\text{lb coal}}\right) \left(6{,}334{,}200 \frac{\text{lb steam}}{\text{hr}}\right)$$

Electrical Output

$$1{,}138{,}832 \text{ KW } \left(3414 \frac{\text{BTU/hr}}{\text{KW}}\right)$$

Efficiency

$$n = \frac{\text{Electrical Output}}{\text{Thermal Input}} = 50.6 \text{ percent}$$

Table 2 presents a comparison of the operating conditions for the Bull Run plant as determined by the cycle analysis outlined above. As far as the plant operation is concerned, four factors stand out as significant improvements when the thermionic topping system is considered.

1. The plant total power output is increased from 914 MW to 1,139 MW.

2. The plant efficiency is increased from 41.3 percent to 50.6 percent.

3. The plant fuel flow rate is increased by only 2 percent.

4. The plant heat rate is reduced from 8,270 BTU/KW-hr to 6,750 BTU/KW-hr.

TABLE 2

COMPARISON OF OPERATING CONDITIONS FOR T.V.A. BULL RUN WITH AND WITHOUT THERMIONIC TOPPING

		Without Topping	With Topping
Feedwater Heater Outlet Conditions (Economizer Inlet)	Pressure	4100 psia	3715 psia
	Temperature	551°F	551°F
	Enthalpy	546 h	546 h
Economizer Outlet	Pressure	4000 psia	3615 psia
	Temperature	650°F	725°F
	Enthalpy	680 h	925 H
Steam to HP Turbine (from Boiler Superheater or Diode)	Pressure	3515 psia	3515 psia
	Temperature	1000°F	1000°F
	Enthalpy	1424 H	1424 H
Steam to IP Turbine (from Boiler Reheater or Diode)	Pressure	540 psia	540 psia
	Temperature	1000°F	1000°F
	Enthalpy	1519 H	1519 H
Secondary Air Inlet	Temperature	110°F	110°F
Exhaust Gas Outlet	Temperature	280°F	280°F
Fuel Flow Rate Percent of Rating		100	102
Efficiency at 100 Percent Rating *		41.3	50.6
Total Output Power	Megawatts	914	1,139
	Percent	100	125
Plant Heat Rate	BTU/KW-hour	8,270	6,750

*Overall Efficiency including Boiler Feed Pump, but without plant loads.

3.6 THERMIONIC DIODE MODULE

The thermionic module is the heart of the topping plant. Our first generation concept is a thermionic module rated at 20 kilowatts electrical output and consisting of an internal series string of 25 separate diodes, each of which delivers about 0.7 volts and 1140 amperes.

The thermionic module uses a silicon carbide envelope as protection against the corrosive effects of the fossil-fuel combustion gases. The outer surface of the envelope is convoluted to develop the surface area needed to transfer sufficient combustion gas heat into the diode module. A heat transfer media delivers the thermal energy to the emitter structure. The collector cooling is accomplished by the superheat and reheat steam. Based on a conversion efficiency of 15 percent, the heat rate of the diode module is about 22,800 BTU/KW-hour.

For a supercritical plant like Bull Run, the economizer heat is adequate to raise the feedwater conditions above the critical value. Thus, only single phase flow exists in the collector cooling portions of the diode. Two diode module designs are used. One design matches the heat transfer requirements of superheat and the other that of reheat. Electrically, there is no difference between the two module types.

For the entire Bull Run plant, a total of 11,200 thermionic modules are projected; 8,170 are used to raise superheat steam and 3,030 are used to raise reheat steam. Based on the use of ten thermionic furnace modules for Bull Run, each furnace will use 1,120 thermionic modules; 817 superheat and 303 reheat.

The diode module operates in the following manner. Combustion gases flow over the exterior of the module. The heat is conveyed with only a few degrees loss, to the emitter surfaces. Electrons are "boiled off" the emitters, which operate at about 2750°F, and enter the collectors with sufficient excess energy to deliver power to an external load. These conditions provide a module conversion efficiency of 15 percent. Thus, 85 percent of the diode heat is delivered to the collector operating at about 1200°F. This heat is then used to raise steam in the conventional superheat (3515 psia, 1000°F) and reheat systems (540 psia, 1000°F).

To obtain the maximum possible output from the thermionic device, it is necessary to minimize the plasma loss and the collector work function. Both these objectives are attained by using cesium vapor in the interelectrode space. The cesium is ionized at the emitter surface and in the gap and overcomes the electron space charge potential, creating a low-loss plasma between the electrodes. In addition, cesium adsorption on the collector results in a low work function surface. Finally, if the cesium pressure is high enough, a partial cesium coating is formed on the emitter, lowering its work function and improving its emission capability. Normally the cesium pressure is controlled by the temperature of an external appendage. Recent work has been done on an adsorption-type cesium reservoir where cesium pressure is governed by the storage of cesium on an extended surface. This adsorption reservoir is installed in the diode itself and operates at temperatures somewhat above that of the collector. This concept simplifies the thermionic module in that it eliminates a cesium appendage and the necessary separate control systems to fix the reservoir temperature.

3.7 THERMIONIC FURNACE

The basic design of the thermionic topping furnace should incorporate the standard power plant boiler components (combustion chamber, superheat and reheat steam generation systems, economizer, etc.) as well as the components specific to the thermionic system (thermionic modules and final air heater). The arrangement should allow for a smooth flow of inlet and exhaust gases with a minimum of structure, and adequate heat transfer surface area in each of the heat exchange systems. Moreover, the design should represent reasonable size and cost considerations to allow for comparison studies with existing equipment.

Based on these criteria, a design has been developed for a first generation thermionic furnace module (Figure 9). The operation is as follows. A forced draft fan delivers inlet air through the air preheater and the final air heater into the main combustion chamber where the pulverized coal is introduced and fired. Swirl in the combustion gases is developed by the flow pattern as the air leaves the final air heater. A cooled separation wall divides the bottom section of the furnace into two parts. The co bustion gases flow down through the first part to the bottom of the furnace where they are directed to the other side of the furnace and flow up over the thermionic modules into an exhaust section. From this point they flow through the final air heater, economizer and air preheater, before entering ducting leading to the precipitators and exhaust stack.

The major part of the slag-content of the combustion gases is removed during the pass from one side of the furnace to the other, prior to heat delivery to the thermioic modules. Under gravity, the molten slag will be collected at the bottom of the furnace.

The temperature of the gases passing over the thermionic modules will be high enough to afford an extremely efficient method of further molten slag removal. This means that coal ash will not build up in any region of the furnace to create blockages or reduce heat transfer effectiveness. If heat transfer surfaces that exhibit little wettability with motten ash are used, the thermionic modules become essentially self-cleaning and the slag trap is used to collect the run-off.

3.8 HEAT EXCHANGERS

Three heat exchange systems are used in the thermionic furnace module; a conventional rotary air preheater, an intermediate economizer which delivers steam above the critical point, and a final air heater designed specifically for high temperature operation (see Figure 9). The design of the air preheater and economizer are not considered to be limiting factors in this study since these units do not represent departures from standard systems operational in present-day power stations. The final air heater is unique for the thermionic topping application.

The design of the final air heater is of critical importance to a plant with thermionic topping. This is the means by which the high temperature potential of the fossil fuel is realized. By heating the combustion air to 2300°F most of the energy in the fuel can be delivered at the high diode operating temperature. The design parameters for the final air heater are; exhaust gas inlet/outlet, 3100°F/1744°F; combustion air inlet/outlet, 555°F/2300°F.

The final air heater design must resolve the two differences between the final air heater and the standard rotary regenerative air heater in present use (as exemplified by the air preheater). Both of these differences arise from one basic factor; operating temperature. The final air heater for the thermionic topping plant must be able to deliver combustion air at an average temperature of 2300°F. To do this, the air heater will handle exhaust gas with an average inlet temperature of 3100°F. These high temperature levels result directly in the two differences mentioned above: (1) heat exchange material and (2) cooling of the rotary drum supports.

The final air heater concept developed for this application uses segments of ribbon-shaped silicon carbide as the heat exchange medium. The rotary drum is segmented and individual silicon carbide configurations are inserted in each compartment. Water-cooling is used for the support ribs, which are built up from a skeleton of chrome-moly tubing. The tubing is surrounded by a soft oxide-base felt-type insulation with a silicon carbide jacket surrounding the entire rib. Rib cooling is accomplished by having cooling water in the skeleton tubing transfer heat radially outward to a condenser-cooling fin system arranged around the outer portion of the rotary drum. The entire final air heater is air-cooled using air from the inlet plenum chamber.

As with the thermionic diode modules, the silicon carbide segements of the final air heater are expected to be self-cleaning. This is accomplished by selecting the operating temperatures of the final air heater such that any ash adhering to the heat transfer surfaces is liquified once every revolution. This run off is then drained into the slag trap.

3.9 POWER CONDITIONING

Introducing thermionic topping into a central power station involves handling the relatively high-power D.C. electrical output of the topping system. For T.V.A. Bull Run, the D.C. output amounts to about 225 MW. It is quite reasonable to consider any candidate power conditioning concept in the light of the following criteria.

1. The system should be able to accept the high-current, low-voltage D.C. output of the thermionic topping system. For T.V.A. Bull Run, the 225 MW thermionic output could reasonably involve 225,000 amperes at 1,000 volts.

2. The system should deliver an output whose characteristics are compatible with the main turbogenerator machines of the plant.

3. The system should have an efficiency as high as possible; preferably over 95 percent.

4. The system should contain as few operating components as possible.

5. The system should be based on well-proven concepts, resulting in maximum reliability.

6. The system should fall within size and cost limits acceptable for electrical utility usage.

Studies of both static and dynamic power conditioning systems, in light of the six criteria listed above, have led to the selection of a D.C. acyclic motor as an ideal solution.

The acyclic motor is a low-voltage, high-current (150,000 amperes typical) D.C. machine capable of operation at power levels of hundreds of megawatts and speeds which enable it to be directly coupled to an 1800 RPM generator shaft, thereby avoiding the necessity of reduction gearing. Information obtained from General Electric Co. indicates that the typical efficiency of an acyclic motor in the 200 megawatt class would be at least 98 percent. For this size machine, the cost would be about $6/ kilowatt. Our study indicates that this method is more efficient and less costly than solid state equipment presently available for this purpose.

3.10 PLANT CONTROL

The control system for a thermionic topped supercritical steam plant is expected to coincide with conventional practice. The only anticipated variation would be in the control of the reheat temperature. Conventional practice for a supercritical one-through boiler is that the combustion control is an integral part of the boiler-turbine-generator unit.

The purpose of this control system is to automatically adapt the generator output to the load demand while maintaining prescribed steam conditions. To achieve this goal, three control modes may be applied to the boiler-turbine unit.

Turbine-following mode. Here demand for a load change is fed directly to the boiler, by adjusting the feedwater and firing rate. As boiler pressure increases, backpressure control on the turbine opens the turbine throttle valves to meet the new load demand. Though a once-through boiler responds quickly, it still cannot make a "step change" to match the load increase; a turbine-following system, therefore, is stable but inherently slow.

Boiler-following mode. In this more conventional control system, load demand is fed to the turbine. The turbine valves respond immediately, as does steam flow. The boiler must then catch up, matching the required rate of steam production as well as accounting for the energy added to or taken from its metal mass in reaching the new load.

While this mode of control responds much more quickly to load changes, the interactions between flow, pressure and steam temperature may result in excessive variations of the latter two should the new load require a change in stored energy beyond the boiler's already small storage capacity. Similarly, utilizing more than a certain proportion of this stored energy may cycle steam flow about the new load point, since pressure control is attained by regulating the feedwater and firing rate, not the turbine valves.

Integrated mode. Here the load demand is applied to both boiler and turbine simultaneously, combining the rapid response of the boiler-following mode with the stability of turbine-following. During a load increase, overfiring (to replace stored energy lost) is proportional to the load error; when the demanded level of generation is reached, this overfiring is reduced to zero. Pressure control is handled by the turbine valves; during transients, pressure deviation is a function of both load error (i.e. the difference between actual and demanded generation) and the available thermal storage capacity. Thus we have an modified boiler-following system, both fast and stable.

Essentially, the low-pressure portion of the revised Bull Run turbogenerator equipment would combine a 450 megawatt turbine and a 225 megawatt acyclic motor to drive a 675 megawatt generator. The station electrical distribution system (transformers, breakers, switchgear, controls, etc.) would be identical to the systems presently used in conventional central stations. Integration of the D.C. output of the thermionic topping system with the conventional A.C. output is achieved in one piece of equipment, the acyclic motor.

Figure 10 presents a schematic of a basic integrated combustion control system such as might be used in a supercritical plant like Bull Run. The system integrates the operation of the boiler and the turbine while minimizing the interactions between the significant process variables; plant electrical output, pressure, and steam temperature. Deviations normally occurring from a load change are anticipated by the integrated control system, which sets the fuel, air and water flows to the values required for the new load rather than waiting for changes in the measured variables to occur and only then beginning to act. The section of the control system peculiar to the thermionic topped plant is shown in heavy lines boxed in phantom and involves the reheat thermionic modules, reheat steam condition and the acyclic motor.

In the basic control system, there are four adjusted variables; feedwater, fuel, air and turbine input, which are regulated to maintain the measured variables at their desired level or set points. These measured variables include generator output, steam pressure, superheat steam temperature, and oxygen in the flue gas for combustion efficiency. The system operates in the following manner.

A change in load is reflected in the Load Demand signal, which is compared with the actual generator output. This comparison, done in the Load Control, may contain frequency, voltage and current components. Any unbalance between the two creates an error signal, which is fed into the Boiler Input and Turbine Valve Controls.

The measured steam pressure is compared with its set point and any resulting unbalance creates an error signal, which is transmitted to the Boiler Input and Turbine Valve Controls, adjusting both the turbine input and the boiler inputs; feedwater, fuel and air. The adjustments are made in opposite directions.

The measured superheat steam temperature is compared with its set point and any resulting unbalance creates an error signal, which adjusts the feedwater-firing rate ratio as required to return steam temperature to the desired level. Changes in feedwater input and firing rate affect steam temperature in about equal amounts, but opposite directions. Since they affect steam pressure and electrical output in the same directions, there is a minimum of interaction on these two parameters.

The final measured variable is the oxygen content of the exhaust gas. It automatically adjusts the fuel-air ratio to maintain optimum combustion efficiency.

The portion of the control system peculiar to the thermionic topped plant is shown in heavy lines in Figure 10 and involves the reheat portion of the steam cycle. Control systems in present use normally employ attemperator sprays to vary the reheat steam temperature. For the topped plant, a relatively straight-forward method of controlling the reheat steam temperature is afforded through use of the acyclic motor. The reheat temperature is measured and compared with its set point. Any unbalance creates an error signal which varies the load presented to the reheat thermionic modules by the acyclic motor. By correcting the resultant output of these thermionic modules, the waste heat going to reheat steam is adjusted to bring the reheat temperature to its set point. Thus, necessary modifications of the control system because of thermionic topping appear to be minimal and do not affect the main superheat, high pressure operations of the plant.

3.11 PLANT ARRANGEMENT

Figures 11 and 12 present the physical arrangement of the furnace modules in the revised Bull Run plant. The drawings are based on plant layouts of Bull Run supplied by T.V.A. An attempt has been made to change these layouts as little as possible. Essentially, the existing Bull Run boilers have been removed and replaced by ten thermionic furnace modules (Figure 9), each of which is rated at about 114 MW total electrical output. The ten modules are arranged in-line in two groups of five each. The ten coal pulverizers and feed systems are the same as thos installed at Bull Run. The acyclic motor, used for power conditioning the thermionic D.C. output, is located on the end of the low-pressure turbogenerator shaft and operates at 1800 RPM.

With reference to Figure 12, the plant elevation, the basic revision to the Bull Run plant becomes evident. Using the thermionic furnace modules, the roof height of the boilerhouse is reduced by about 100 feet. This volume reduction amounts to about 4 million cubic feet.

3.12 ECONOMIC ANALYSIS

Based on the results of the steam cycle calculations and cost figures supplied by T.V.A., an estimated cost comparison has been prepared for the T.V.A. Bull Run plant both with and without the thermionic topping system outlined in this report. This cost comparison is presented in Table 3.

The "Without Topping" figures were supplied by the T.V.A. These figures were modified, where necessary, to reflect changes brought about by introduction of the thermionic topping system. The changes are discussed in more detail below.

Land and Land Rights - No change in cost.

Structures and Improvements - The cost attributable to the powerhouse has been changed. Using the thermionic furnace modules, the interior volume of the boilerhouse is reduced by about 4 million cubic feet. Since the existing Bull Run Powerhouse has a volume of about 14 million cubic feet and cost $15,338,000, the pro-rated savings amounts to about $4,000,000.

Boiler Plant - The cost of the thermionic diode modules is included under this category. Our estimate of this cost, applicable on a production basis after initial development work, is about $100/KW of electrical output, or $2,250,000 for the 225,000KW output of the entire plant. While the Bull Run boiler costs are entered without change, it must be noted that the boiler cost distribution is quite different for the topped plant. Superheater and reheater costs, included in boiler costs for Bull Run, are part of the thermionic diode module costs for the topped plant. Boiler costs for the topped plant include the main furnace structure, the economizer system and the final air heater (see Figure 9). For both Bull Run and the topped plant, the forced draft fan and the air preheater are included as part of draft equipment costs. Our estimates for the remaining three main items are:Main furnace structure $792,000, economizer system $500,000, final air heater $800,000; totaling $2,092,000 for each furnace module or $20,920,000 for the entire plant. Beacuse of the increased coal rate for the thermionic plant (0.102 lb coal/lb steam as opposed to the 0.1 lb coal/lb steam for Bull Run), the following cost factors were increased by 2 percent; draft equipment, coal handling and storage facilities, fuel burning facilities, ash handling equipment, and boiler plant boards, instruments and controls.

Turbogenerator Plant - Two cost items change in this category. The cost of the acyclic motor used for power conditioning of the plant thermionic output is included for the plant with topping. General Electric has indicated that for the power level of 225,000 KW, the acyclic motor cost would be $6/KW. Also, in the topped plant, the acyclic motor will drive a generator in tandem with the low pressure turbine. A larger generator (by 225,000 KW) will be used. The differential cost for this larger generator will be $6/KW.

Accessory Electrical Equipment - All the items in this category have been raised by 25 percent because of the 25 percent higher plant output resulting from the use of the thermionic topping system.

Miscellaneous Power Plant Equipment - No change in cost.

Transmission Plant - This cost has been raised 25 percent because of the 25 percent higher plant output resulting from the use of the thermionic topping system.

As Table 3 shows, the total cost of the Bull Run plant is estimated at $142,500,000 without thermionic topping and $159,307,000 with thermionic topping. This increased cost raises the plant output from 913,832 KW to 1,138,832 KW. The result is that the total cost in $/KW is lowered from $155.94/KW to $141.17/KW by the thermionic topping system. This represents a savings of $14.77/KW or 9.5 percent.

Aside from plant cost, a further significant cost advantage is brough about by the increase in plant efficiency from 41.3 to 50.6 percent. Using a reasonable basic coal price of 18 cents per million BTU, and assuming a 100 percent load factor for a plant of Bull Run size (1,139 megawatts), the fuel costs may be calculated for the plant without thermionic topping (41.3 percent efficiency) and with thermionic topping (50.6 percent efficiency).

Annual Fuel Cost (without topping)	$14,850,000.
Annual Fuel Cost (with topping)	$12,120,000.

The savings in fuel cost alone, is $ 2,730,000. This figure affords a convenient approach to obtaining the fuel savings corresponding to any load factor. For example, for an 80% load factor, the fuel savings would be 0.8 (2,730,000) or $2,184,000.

TABLE 3

COST COMPARISON OF T.V.A. BULL RUN PLANT
914 MW WITHOUT THERMIONIC TOPPING
1,349 MW WITH THERMIONIC TOPPING

Estimated Total Cost
(in thousands of dollars)

Item	Without Topping	With Topping
Land and Land Rights		
Purchase Price of land (including acquisition)	1,150	1,150
Relocate highways and highway bridges	50	50
Relocate railways and railway bridges	524	524
Relocate and protect other structures & improvements	60	60
	1,784	1,784
Structures and Improvements		
Preparation of site	286	286
General Yard Improvements	3,448	3,448
Powerhouse	15,338	11,338
Miscellaneous buildings	349	349
Waterfront Improvements	823	823
	20,244	16,244
Boiler Plant		
Thermionic Diode Modules	-0-	22,500
Boilers and Accessories	20,920	20,920
Draft Equipment	7,440	7,589
Feedwater equipment	2,880	2,880
Coal handling and storage facilities	11,388	11,616
Fuel burning facilities	3,327	3,394
Ash handling equipment	2,551	2,602
Water supply and treating system	972	972
Boiler plant boards, instruments and controls	2,881	2,939
Boiler plant piping	4,100	4,100
	56,459	79,512

TABLE 3 (Continued)

	Without Topping	With Topping
Turbogenerator Plant		
Acyclic Motor	-0-	1,350
Turbogenerators	17,453	18,803
Circulating water system	1,778	1,778
Condensers and auxiliaries	1,257	1,257
Central lubrication system	87	87
Turbine plant boards, instruments and controls	64	64
Turbine plant piping	79	79
Auxiliary equipment for generators	180	180
Other turbine plant equipment	25	25
	20,923	23,623
Accessory Electrical Equipment		
Switchgear	616	770
Switchboards	1,443	1,804
Protective Equipment	114	143
Electrical structures	423	529
Conduit	1,193	1,491
Power and control wiring	1,581	1,976
Station service equipment	680	850
	6,050	7,563
Miscellaneous Power Plant Equipment		
Station maintenance equipment	533	533
Cranes and hoisting equipment	819	819
Compressed air and vacuum cleaning equipment	202	202
Other miscellaneous equipment	539	539
Accumulated depreciation on permanent equipment	-16	-16
	2,077	2,077
Total Direct Cost of Steam Plant and Land	107,537	123,240
Transmission plant	4,415	5,519
Communication Equipment	182	182
Total Direct Cost	112,134	128,941
General Expense	20,593	20,593
Interest During Construction	9,773	11,238
Total Cost	142,500	160,772
PLANT OUTPUT (KILOWATTS)	913,832	1,138,832
TOTAL COST ($ PER KILOWATT)	155.94	141.17

4.0 EXPERIMENTAL AND MATERIALS PROGRAM

The second part of the overall program effort involved the design, construction and test of thermionic converters. The testing included device operation in a coal-fired environment. In turn, the demonstration of a viable thermionic converter design was dependent upon a concerted materials development effort, the major portion of which was devoted to the development of an emitter envelope capable of protecting the converter against the combustion gas and coal slag environment.

Included in this experimental program was work on the candidate material for the final air heater. While this heat exchange medium need not be impervious to the combustion gases, it is improtant that this material maintain reasonable structural integrity when subjected to the effects of temperature cycling in a coal-fired environment. Testing indicated that silicon carbide ceramic would prove satisfactory as the heat exchanger medium for a rotary type final air heater.

To realistically conduct the coal-fired testing, two facilities were prepared. The first was designed to test the heat exchanger material and included automatic temperature-cycling capability. The second was an adaptation of the propane-fired furnace normally used for testing thermionic converters at CCC. This furnace was modified to allow pulverized coal to be fed continuously into the furnace combustion chamber.

A total of 18 thermionic converters were tested as part of our program. Power output levels of up to 133 watts and operating lifetimes of up to 318 hours were obtained from these converters. Two diodes were operated in a coal-fired environment; one of them operating for 127 hours (85 hours in coal-fired environment) at 112 watts output, the other operated for 6 hours in coal. Both tests were terminated by cold end failures. The hot end of both converters appeared to be unaffected by the coal slag. During the test program, diode failures were concentrated at the cold end of the converter. Recent design work was directed to this area and has progressed to the point where the solution of the "cold-end" problem appears to be near.

4.1 THERMIONIC DIODE PROGRAM

Progressive testing of thermionic diodes, from operation in fossil-fuel gas to power generation in a coal-fired furnace, was performed as part of this program. Initially, testing was devoted to diode performance in a propane-fired furnace, with combustion gases at about 3100°F. A series of these converters were run with various combinations of protective coatings, and emitter and collector surfaces.

The earliest tests were performed in a propane-fired furnace on test converters with protective envelopes of iridium, overcoated with plasma-sprayed and CVD (Chemical Vapor Deposited) aluminum oxide. The first concern with the iridium-alumina protective systems was that of hydrogen permeation through the protective shell, which can generate a water cycle within the diode, with ultimate shorting. Hydrogen permeation would also increase the pressure within the diode, affecting the peak efficiency. The second concern with the iridium-alumina system was the attack upon alumina and iridium to be expected from a silicious environment, such as coal ash slag.

As the testing progressed along with our materials effort, the protective system that showed the greatest potential was a CVD silicon carbide coating over tungsten.

Our initial difficulties in obtaining flawless silicon carbide protective envelopes led us to conclude that more effective control of silicon carbide properties, through the CVD synthesis parameters, was essential to the fabrication of diodes. A study of synthesis parameters and the resultant properties of CVD silicon carbide was carried out in cooperation with San Fernando Laboratories in California. Specimens were characterized according to surface appearance, deposit thickness, metallography, burst testing, and chemical analysis. About two hundred pictures of surface features and an equal number of photomicrographs, from corresponding locations, were taken. Some correspondence between surface appearance and microsturcture was apparent in extreme cases, but the poor sensitivity of visual surface inspection rendered it questionable as a device for evaluating structural quality.

Chemical analyses of sixty tubular segments were rendered for comparison with structural quality, as defined by microstructure. "Wet" analyses for total silicon, total carbon and free carbon were provided. The numerical variations in total silicon and total carbon generally fell

within the absolute sensitivity limits of analysis for these elements in silicon carbide, which were ±2%. Since good and bad structures could be found in the series, and all fell within the sensitivity limits both for total carbon and total silicon, the analysis could not effectively be correlated with silicon carbide structure.

Burst tests were performed on specimen segments without any strong indications of relationships between appearance, microstructure, chemistry, or material strength. A broad-spread in burst stress values were obtained. The most significant features of the testing were the high burst strengths which could be achieved with CVD silicon carbide. Five specimens has tensile burst stresses above 7,000 psi, and one was over 10,000 psi.

Despite these difficulties, converter testing confirmed the following characteristics of the silicon carbide envelope.

1. Greater protective shell lifetime.
2. Hydrogen permeation below levels of any significance.
3. Stability in high-temperature oxidizing environments.
4. Compatibility with silicious materials.
5. Potential economy of synthesis and fabrications.

One of our initial aims in this program involved the testing of thermionic converters in a coal-fired furnace facility at Combustion Engineering Inc. A sketch of this facility is shown in Figure 13. However, while modification work was being started on this furnace, our initial materials research and converter testing made it apparent that performance of tests outside of the CCC laboratories would deprive us of the close control we deemed necessary for proper evaluation of results and improvement of design. Coupled with our experience with coal-environment testing of the silicon carbide final air heater material (described in Section 4.2), we decided to revise our conventional propane-fired test furnace to include the capability of using pulverized coal. A schematic of this test furnace is shown in Figure 14. The pulverized coal is continuously injected into the furnace combustion chamber. All initial testing of converters was performed in this type furnace with the exception that the pulverized coal feeder was not used

Table 4 presents a summary of the thermionic converter testing performed under this program. A total of 18 converters were tested; two of which (Nos. 495 and 498) were operated in the coal-fired environment. The basic design of the test converter is shown in Figure 15. The various design materials and metal-ceramic seal configurations are noted. In the fabrication of the test converters, the weld joints were made by electron-beam welding techniques, to avoid any possible contamination of the components.

As shown in Table 4, the converters tested in the propane-fired furnace delivered up to 133 watts, for a period of 100 to 318 hours at temperature. The design output for the converter shown in Figure 15 is about 100 watts.

TABLE 4

SUMMARY OF THERMIONIC CONVERTER TESTING
(Gas at 3100°F, Emitter at 2500°F)

DIODE TEST	TEST DATE START	TEST DATE STOP	PROTECTIVE ENVELOPE	TEST HOURS	POWER OUTPUT	LOCATION OF FAILURE
479	6-1-67	6-15-67	Silicon Carbide	48	40	Cold End
480	6-27-67	6-29-67	Silicon Carbide	6	NT	Cold End
481	8-28-67	8-28-67	Iridium with CVD Alumina	3	NT	(Short)
482	9-11-67	9-16-67	Iridium with Plasma Spray Alumina	19.5	32	Output Degradation (Short)
483	9-23-67	9-25-67	Silicon Carbide	5	NT	Hot End
484	9-30-67	10-3-67	Silicon Carbide	16.5	NT	Hot End
485	10-11-67	10-13-67	Silicon Carbide	8	30	Hot End (SiC Failure)
487	10-18-67	10-19-67	Silicon Carbide	8	NT	Cold End
488	11-6-67	11-21-67	Silicon Carbide	61	90	Leak in Nickel weld
489	1-26-68	2-24-68	Silicon Carbide	318	70	Cold End
490	2-26-68	3-8-68	Silicon Carbide	102	95	Cold End
492	3-26-68	3-27-68	Silicon Carbide	19	NT	Cold End

TABLE 4 (Continued)

DIODE TEST	TEST DATE START	STOP	PROTECTIVE ENVELOPE	TEST HOURS	POWER OUTPUT	LOCATION OF FAILURE
493	4-11-68	4-19-68	Silicon Carbide	120	105	Cold End
494	4-27-68	4-30-68	Silicon Carbide	10	133	Hot End
495	5-13-68	5-22-68	Silicon Carbide	6 *	94	Cold End
496	6-3-68	6-7-68	Silicon Carbide	4	66	Free-Standing Shell
497	7-15-68	7-18-68	Silicon Carbide	9	NT	Separation at the Mo Si_2, 60% of Surface
498	7-25-68	8-21-68	Silicon Carbide	127 **	112	Cold End

NT = Not Tested
* Includes 6 hours of operation in coal-fired environment
** Includes 85 hours of operation in coal-fired environment

The most common failure mode was by breach of the silicon carbide envelope, not in the hot region, but at the relatively cold end of the emitter shell. Figure 16 shows a typical envelope failure. Variations in structures, showing increasing free carbon toward the cold end of the tubes, are shown in Figures 17 through 26.

The failure of converter No. 489 (Figures 17 through 21) occurred at the cold end of the protective envelope (operating temperatures 1000 - 1300°F) and is of particular interest since the main body of the envelope was still intact after operation for 318 hours. No decline in power output had taken place during the test. Examination of converter No. 489 after envelope failure revealed a progressive oxidation of the outer surface, stemming from a breach of the silicon carbide envelope. Figures 17 through 21 show microsections of the envelope, progressing in one inch intervals from the hot end of the diode to the cold end where failure took place. In all instances, the inner surfaces are at the left of the figure. A change in structure is apparent, revealing increasing quantities of a second phase toward the cold end. The secondary phase has been associated with excessively high carbon content in the silicon carbide envelope. The phase has tended to occur toward the open (cold) end of the envelopes during their fabrication, and is believed to be uncombined carbon incorporated within the envelope structure.

One possible mode of penetration through the envelope would be the oxidation and removal of the incorporated free carbon as CO or CO_2, permitting continued ingress of the atmosphere, until the envelope has been breached. Once this has happened, the emitter would be oxidized in the vicinity of the breach, and the increased volume of solid material could cause rupture to the envelope, leading progressively to further oxidation.

Metallographic examination of converter No. 490, after 102 hours of operation, yielded similar results. Figures 22 through 25 indicate progressively increasing carbon content toward the cold end of the silicon carbide envelope. Again, this free carbon represented an oxidizable medium to permit the envelope to be breached. Figure 26 shows a chip from the failure region of the envelope of converter No. 490. It is interesting to note the holes in the envelope structure which the photograph clearly reveals. Such porosity, associated with free carbon, will permit oxidation and failure of the underlying emitter surface.

Oxygen penetration through, or along, a carbon-rich zone has certainly been a failure mode. A second failure mode must alsc be considered; that of oxygen penetrating the joint region between the emitter and the protective envelope. It is essential that this junction be gas-tight to assure protection of the emitter. If this joint were to permit entry of oxygen, some oxidation of the emitter could occur. Oxide, built up at the emitter-envelope interface, could exert pressures sufficient to rupture the envelope. The mechanism, therefore would be (a) oxygen penetration at the joint and (b) subsequent penetration along the emitter-envelope interface, producing expanded oxides which could burst the silicon carbide layer.

The first requirement for this failure mechanism to operate would be a penetrable joint. The second requirement would be a penetrable envelope-emitter interface. The second condition might be fulfilled by direct attack along the interface by oxygen, although the oxides would tend to impede further passage of oxygen. The second condition could also be fulfilled by a loose bond between the emitter and its envelope.

In any event, if such a failure mode exists, it should be prevented by obstructing gas entry at the point. Then, whether or not a tight bond exists between emitter and envelope, no oxygen will be present to operate on the interface, and this type of failure would be avoided.

The evidence of the cold-end failures indicated that our future efforts should be closely concerned with the following:

1. Control of the silicon carbide envelope synthesis to achieve a more uniform structure and eliminate free carbon from the "open" end.

2. Improvement of the joint, to reduce possibilities of oxygen penetration at the envelope-emitter interface..

When testing in the coal-fired furnace (Figure 14) was performed, failure of the shell was again observed to occur at the "cold" end, rather than in the hot, slagging region of the converters (Nos. 495 and 498). These results indicated again that the prime concern for extending life performance was not with resistance to coal slag, but rather in the homogeneity and cold-end sealing of the silicon carbide envelope, as stated above. Typical pictures of the

converters after periods of coal firing are shown in Figures 27, 28, and 29. As shown in Figure 29, converter No. 498 was run for 127 hours, 85 hours of which were in the coal-fired environment, with no appreciable attack by slag.

At this point, although greater control over homogeneity and cold end sealing was required, the ability of the envelope material to resist coal-fired environments, while thermionic power is being generated, had been demonstrated for moderate periods of time. No indication of hot end failure due to coal slag effects was apparent.

Our most recent efforts have been directed toward the free-standing protective element concept, wherein the silicon carbide shell is not deposited directly on the tungsten emitter, but is self-supporting, and transmits its heat to the emitter via a molten metal medium. Studies thus far have indicated tin to be the metal medium most compatible with silicon carbide, tungsten and molybdenum.

Figure 30 shows a schematic employing the free-standing concept. A tin interlayer between the diode and shell serves to convey heat, while a molten glass reservoir serves as a flexible seal to protect the tin and the nickel-tungsten emitter joint from oxidation.

This concept was undertaken, using a free-standing shell of slip cast silicon carbide, overcoated with gas-tight CVD silicon carbide. It was noted after several days operation in the furnace that a heavy build-up of oxides of tin developed below the glass-tin interface, binding the diode strongly into the envelope. The avenue by which oxygen reached the tin was through the porous slip casting, between the glass and the impervious CVD outer coating.

Free-standing envelopes, totally composed of (fully dense) CVD silicon carbide, would not be vulnerable to such penetration. Free-standing, leak tight CVD structures, without slip cast substrates, have since been generated and hold promise as a solution to the converter "cold-end" problem encountered in our previous testing.

4.2 SILICON CARBIDE SLAG TESTING

As described previously in this report, the final air heater concept developed for the thermionic topped central station uses segments of silicon carbide ceramic as the heat exchange medium. The experimental aspects of this choice involved the testing of silicon carbide samples under conditions simulating final air heater operation. These conditions include temperature cycling and coal ash deposition. An automatic temperature cycling test facility was designed and built to evaluate tubular samples of silicon carbide. Figure 31 presents two views of this facility.

During testing, a temperature cycle consisted of directing the output of two oxygen-acetylene torches at the test sample so that the temperature of the sample rose to about 2800°F, in about one minute; after which the torches were shut-off to allow for a two-minute cool-down to about 700°F. Coal ash was deposited on the surface of the test sample during the cool-down portion of the test cycle.

The tubular test sample was inserted in a water-cooled furnace, two walls of which were cut away to allow the flames from the two water-cooled torches to play directly upon the test sample. A thermocouple was installed inside the tubular test sample to monitor its temperature. Each torch was coupled with a pilot light flame to provide ignition. Oxygen and acetylene flow to the torches was controlled by timer-actuated solenoid valves. As stated above the torches were fired for one minute, followed by a two minute cool-down period. For cool-down, the acetylene flow was stopped first. The oxygen flow was allowed to continue for five seconds to purge the torch line and prevent possible flash-back.

The automatic feeder system was capable of operation with either pulverized coal or coal ash. Two test modes were available.

1. Coal- When used with pulverized coal, the feeder allowed continuous introduction of the coal into the flame area. When operating in this mode, torch operation was continuous with no temperature cycling.

2. Coal Ash- When used with coal ash, the feeder allowed automatic introduction of coal ash onto the test sample. The coal ash was introduced for a period of five seconds, starting at the point of torch shut-off.

Two tubular samples of silicon carbide ceramic were tested under the above conditions. The first sample was temperature cycled 34 times. Unfortunately, the sample was broken inadvertantly while being removed from the test furnace for examination. Solidified coal ash was evident on the tube surface, but sectioning and metallographic examination of the test sample showed no coal ash penetration of the silicon carbide.

The second silicon carbide sample was temperature cycled over 7,300 times. Upon examination, the only visible effect on the silicon carbide was an erosion of about 0.02 inch, where the tip of one of the oxygen-acetylene torches was very close to the sample. It was apparent that the temperature of this point was considerably higher than the measured temperature of the test sample and certainly higher than any temperature that would be encountered during operation of the final air heater. As before, solidified coal ash was evident on the tube surface, but sectioning and metallographic examination of this second test sample showed no coal ash penetration of the silicon carbide.

The solidified coal ash observed on the test sample was a result of the final cool-down. During the temperature cycling, good run-off to the coal ash was observed at the high temperatures, leading to the conclusion that the final air heater would indeed be self-cleaning. Build-up of coal ash on the final air heater following a shut-down of the station would be avoided by keeping up station heat using gas or oil as a final fuel before shut-down.

The testing clearly indicated that the silicon carbide ceramic would prove satisfactory as the heat exchange medium for a rotary type final air heater.

5.0 1,000 WATT THERMIONIC MODULE AND COAL-FIRED FURANCE

As the next stage of the program to establish the feasibility and practicality of thermionic topping, a multi-diode thermionic module should be designed, built and tested in a coal-fired furnace. As outlined previously, it is not necessary for the thermionic module to be full-size but rather, the multi-diode design and the heat transfer characteristics of the emitter and collector systems must be verified. Therefore, the test system may be a much simplified version of the thermionic furnace module.

A special furnace is required for this purpose; it functions similarly to that of a full-scale thermionic power plant with two exceptions. These are (1) there is no need for an economizer and (2) a static final air heater may be used rather than undertaking the development of a rotary heat exchanger installation. These simplifications will not negate the evaluation of the thermionic module performance and characteristics of the emitter and collector heat transfer systems.

A 1,000 watt, multi-element thermionic module was chosen as a reasonably-sized version of the 20 kilowatt module required for a full-scale central station. This new thermionic module differs from the converters built and tested during the present program (see Section 4) by its multi-diode feature and its increased output (100 to 1,000 watts). The proposed size is adequate to test all features of the 20 kilowatt module, and provides a good vehicle for future testing of a model power plant.

To obtain a better appreciation of design and physical configuration, a mock-up was built of the 1,000 watt thermionic module and the coal-fired furnace. Figures 32 and 33 show the complete mock-up. Figure 33 presents the internal arrangement. The system is completely self-contained, and includes the thermionic module, static heat exchanger, two motor-driven, variable-speed coal feeders and forced draft fan.

The assembled thermionic module is shown in Figure 34. The finned section receives heat from the combustion products and transfers it to the emitters of the individual thermionic converters. The thermionic module consists of 20 individual diodes, connected in series to deliver 14 volts at about 75 amperes. The module is cooled by steam in a manner typical of central station use.

Figure 35 shows the multi-diode collector configuration removed from the emitter housing. The rings mounted to each collector segment provide the series connections to the adjoining emitter. A simulated collector cooling coil is shown removed from the collector. Steam at approximately 3,500 psi and 1,000°F would be used to cool the module and simulate the steam cooling of a full scale central station.

A schematic of the furnace arrangement is shown in Figure 36. Combustion air is circulated by the forced draft fan through the heat exchanger to the combustion chamber. Coal is added and the molten slag is tapped off at the bottom of the furnace. The combustion gases flow upward over the module envelope, providing heat to the thermionic module, and then exhaust through the heat exchanger. This system is similar to the expected full-scale system with the exception of an economizer.

The heat exchanger, shown in Figure 37, is a simple static counterflow unit rather than the rotary unit projected for the central station. To accommodate the expected slag build-up problem, the furnace would be shut down occasionally and the heat exchanger cleaned. In the full-scale unit, the rotary heat exchanger would be self-cleaning.

6.0 CONCLUSIONS

Our work prompts three observations. First, thermionic energy conversion does have a place in the field of high-power electrical generation. When used in a topping system, significant improvements are indicated in both efficiency ratings and capital costs. For the T.V.A. Bull Run plant, the station output and efficiency can be increased from 914 MW at 41.3 percent to 1,139 MW at 50.6 percent. These improvements are accompanied by an estimated minimum saving of about 10 percent in total direct plant cost and an annual fuel saving of up to $2.7 million.

Secondly, the technology will be forthcoming for the production of thermionic converters with adequate lifetime for this application. The protective barrier technology should be developed concurrently with system development. A short range objective would be the design for the multiple-diode thermionic module.

Third, we do have the prospect of better utilization of our coal resources with an attendant decrease in thermal and atmospheric pollution in relation to power generated. In view of these findings, it appears that thermionic topping in central power station might be both economically and socialogically attractive.

A good deal of work still remains to develop a multiple-diode thermionic module for this application, and conduct the experimental and material programs needed to establish the viability of the module design. An important step beyond the current effort is fabrication and test of a small scale coal-fired test system.

The thermionic module should be of the multiple-diode type but not necessarily a 20 kilowatt unit. The arrangement of the test system should be a miniature simulation of the furnace module design except for the fact that a turbogenerator need not be included. Measurements of the temperature conditions and steam output from the thermionic modules would provide an adequate evaluation of performance.

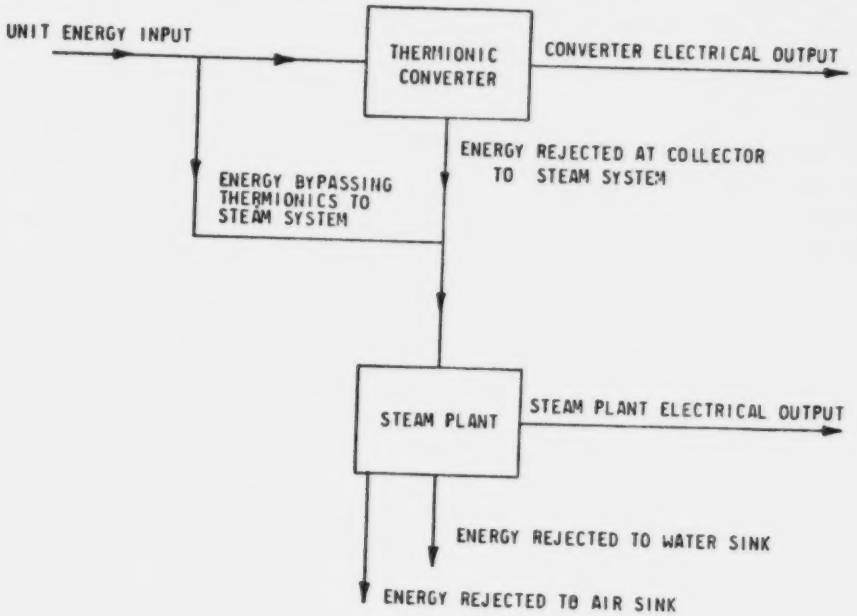

UNIT ENERGY INPUT
THERMIONIC CONVERTER
CONVERTER ELECTRICAL OUTPUT
ENERGY REJECTED AT COLLECTOR TO STEAM SYSTEM
ENERGY BYPASSING THERMIONICS TO STEAM SYSTEM
STEAM PLANT
STEAM PLANT ELECTRICAL OUTPUT
ENERGY REJECTED TO WATER SINK
ENERGY REJECTED TO AIR SINK

FIGURE 1
SIMPLIFIED ENERGY DIAGRAM OF A THERMIONIC TOPPING SYSTEM

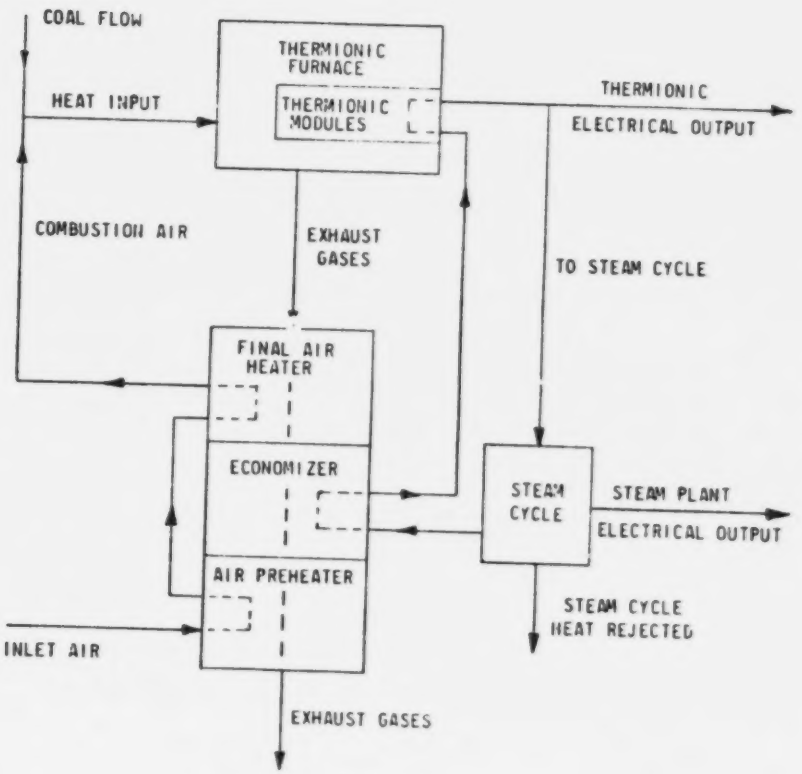


FIGURE 2
BLOCK DIAGRAM OF A THERMIONIC TOPPING SYSTEM

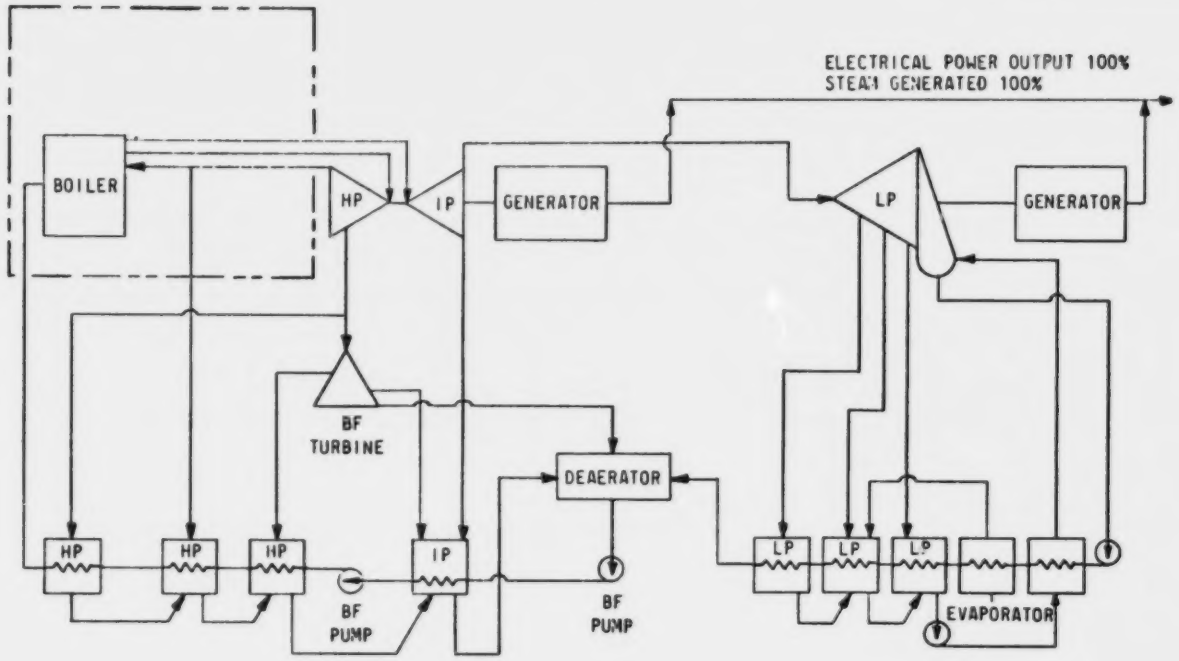


FIGURE 3
COAL-FIRED CENTRAL STATION WITHOUT THERMIONIC TOPPING

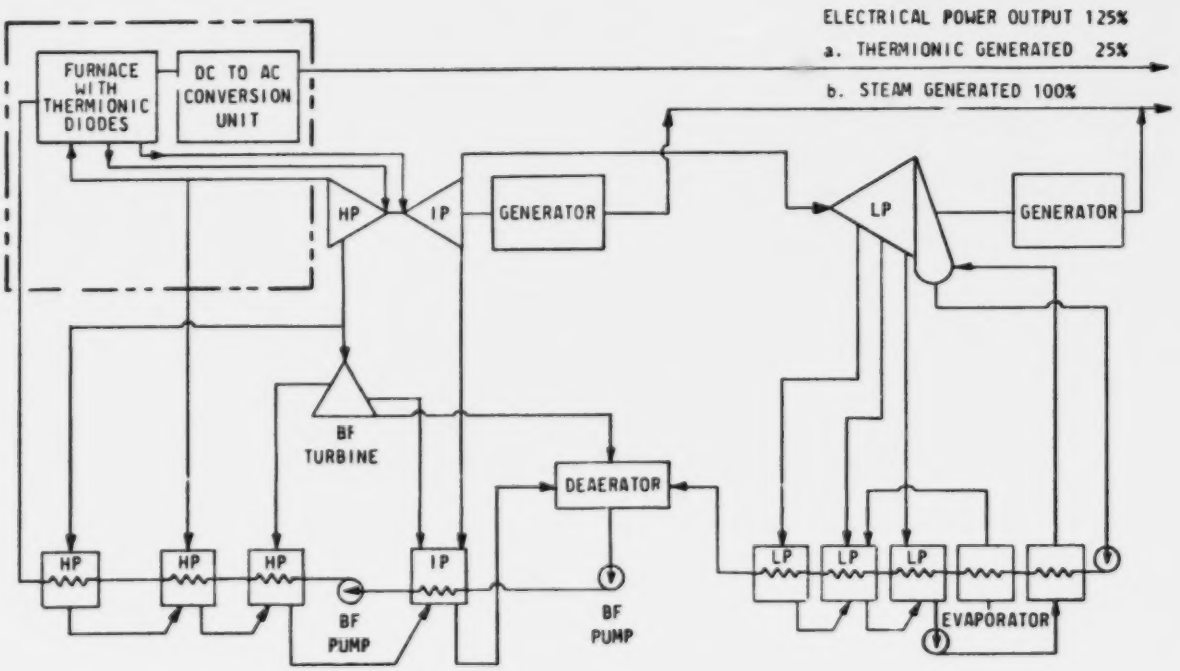


FIGURE 4
COAL-FIRED CENTRAL STATION WITH THERMIONIC TOPPING

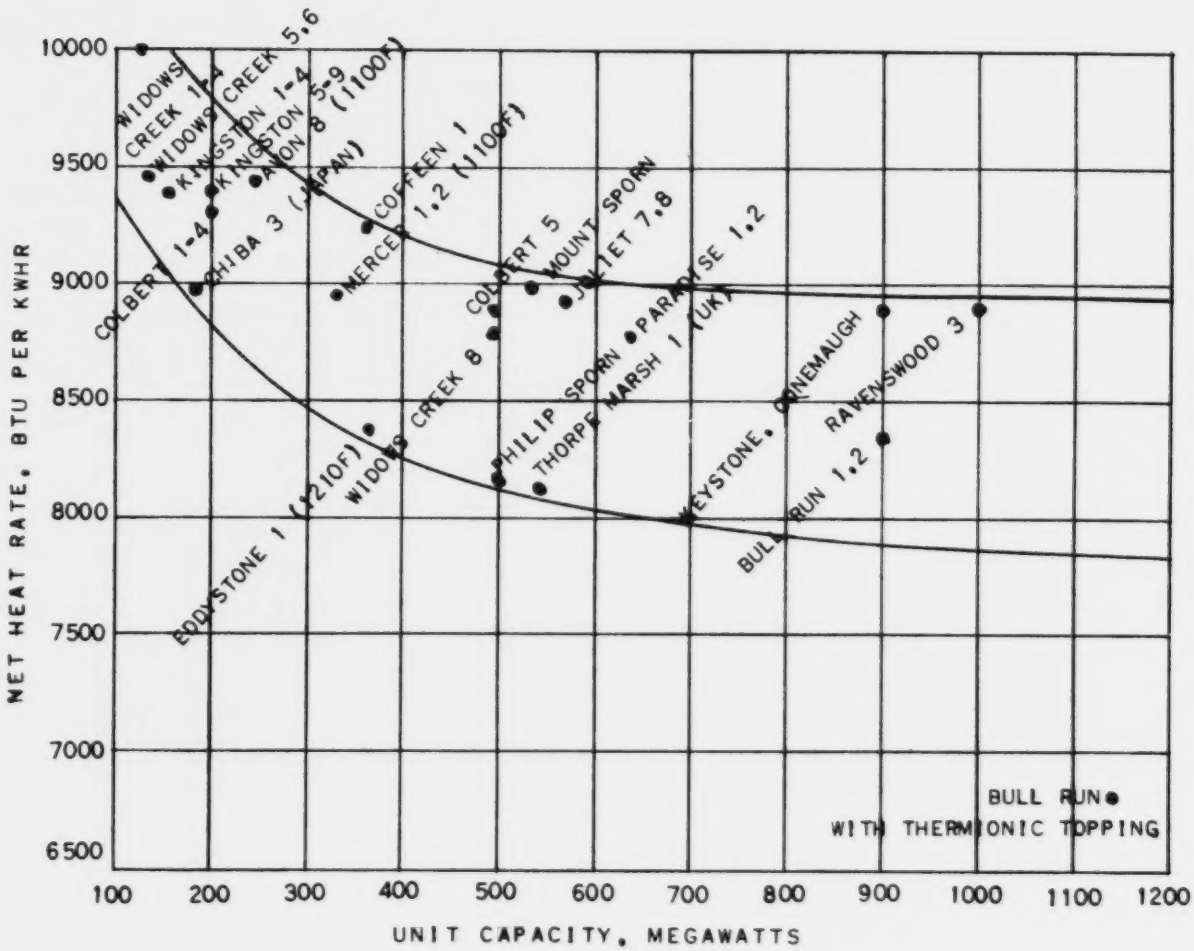
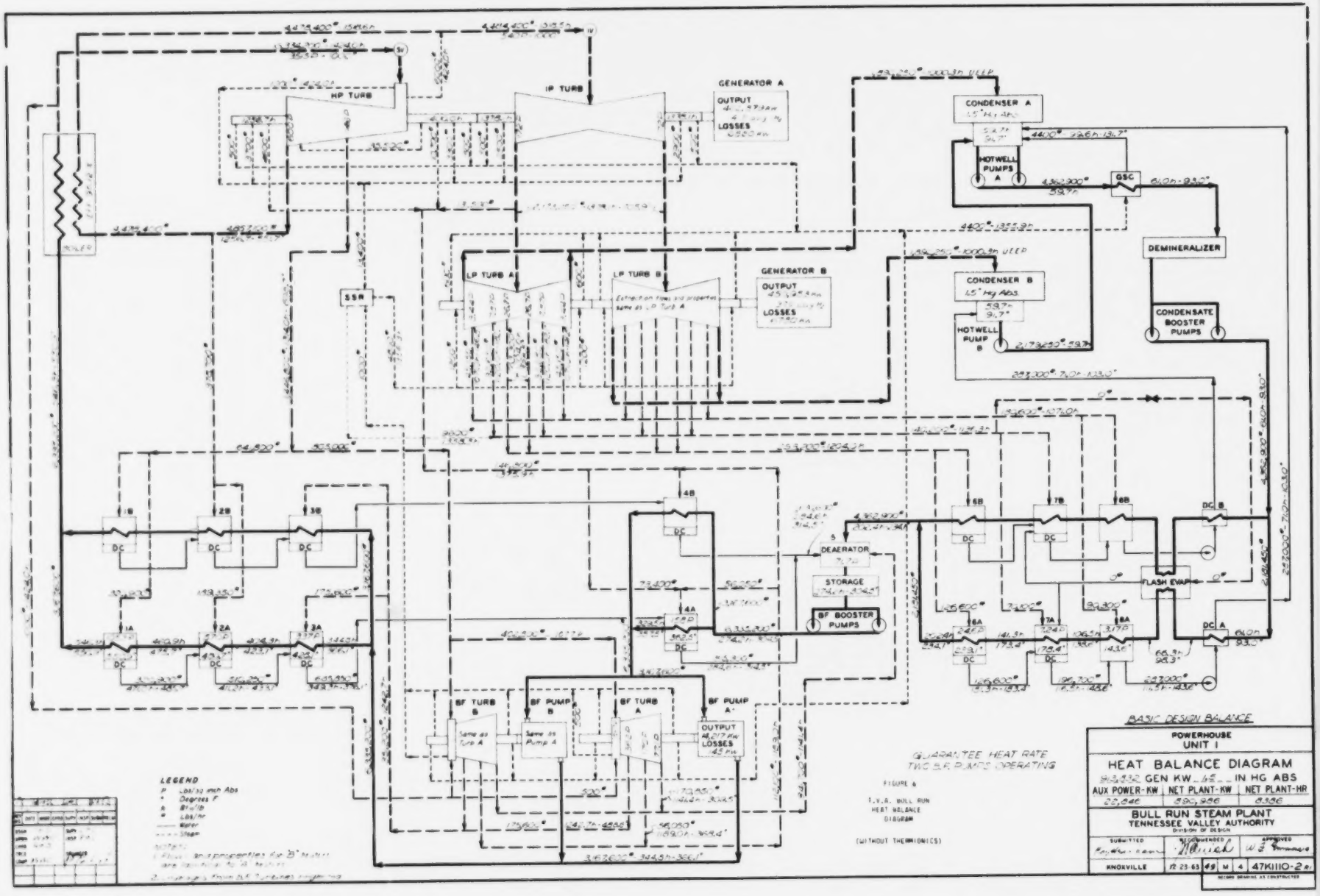


FIGURE 5

STATION HEAT RATE AS FUNCTION OF CAPACITY


HP TURB
IP TURB
GENERATOR A
OUTPUT
LOSSES
CONDENSER A
HOTWELL PUMPS A
GSC
DEMINERALIZER
LP TURB A
LP TURB B
GENERATOR B
CONDENSER B
HOTWELL PUMP B
CONDENSATE BOOSTER PUMPS
SSR
DEAERATOR
STORAGE
BF BOOSTER PUMPS
FLASH EVAP
BF TURB B
BF PUMP B
BF TURB A
BF PUMP A
OUTPUT 46,217 Kw
LOSSES 45 Kw
LEGEND
P Lbs/sq inch Abs
t Degrees F
h Btu/lb
W Lbs/hr
Water
Steam
GUARANTEE HEAT RATE
TWO S.G. PUMPS OPERATING
FIGURE 6
T.V.A. BULL RUN
HEAT BALANCE
DIAGRAM
(WITHOUT THERMIONICS)
BASIC DESIGN BALANCE
POWERHOUSE
UNIT 1
HEAT BALANCE DIAGRAM
913,332 GEN KW 45 IN HG ABS
AUX POWER-KW
NET PLANT-KW
NET PLANT-HR
22,846
890,296
8396
BULL RUN STEAM PLANT
TENNESSEE VALLEY AUTHORITY
DIVISION OF DESIGN
SUBMITTED
RECOMMENDED
APPROVED
KNOXVILLE
12 23 63
49
M
4
47K1110-2 R
RECORD DRAWING AS CONSTRUCTED

5 - 6 FW HEAT FROM TURBINE BLEEDS
6 - 1 ECONOMIZER AND SUPERHEATER
2 - 3 REHEATER
1 - 2 HP TURBINE EXPANSION
3 - 3A IP TURBINE EXPANSION
3A - 4 LP TURBINE EXPANSION

PT	TEMP °F	PRESS. PSIA	ENTHALPY BTU/LB
1	1000	3515	1424
2	551.7	600	1256.7
3	1000	540	1518.6
3A	705.9	172	1378.1
4		*	1000.3
5	91.7	*	59.7
6	550.9	4100	546.3

* PRESSURE IS 1.5" Hg

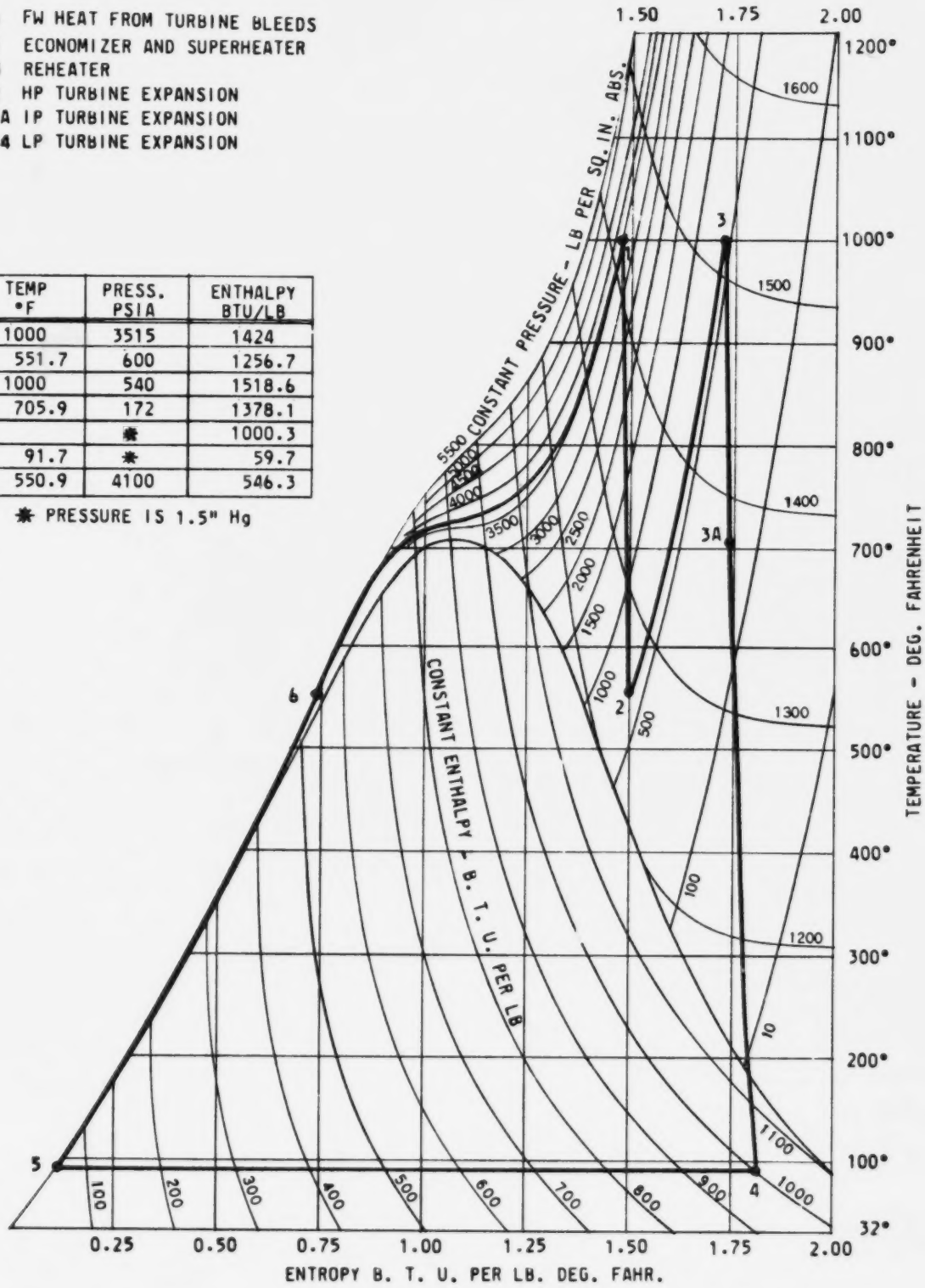


FIGURE 7

T. V. A. BULL RUN TEMPERATURE - ENTROPY CHART (WITHOUT TOPPING)

5 - 6 FW HEAT FROM TURBINE BLEEDS
6 - 7 ECONOMIZER (HEAT FROM EXHAUST GASES)
7 - 1 SUPERHEATER (HEAT FROM THERMIONIC CONVERTERS)
2 - 3 REHEATER (HEAT FROM THERMIONIC CONVERTERS)
1 - 2 HP TURBINE EXPANSION
3 - 3A IP TURBINE EXPANSION
3A - 4 LP TURBINE EXPANSION

PT	TEMP °F	PRESS. PSIA	ENTHALPY BTU/LB
1	1000	3515	1424
2	551.7	600	1256.7
3	1000	540	1518.6
3A	705.9	172	1378.1
4		*	1000.3
5	91.7	*	59.7
6	550.9	3715	546.3
7	725	3615	925

* PRESSURE IS 1.5" Hg

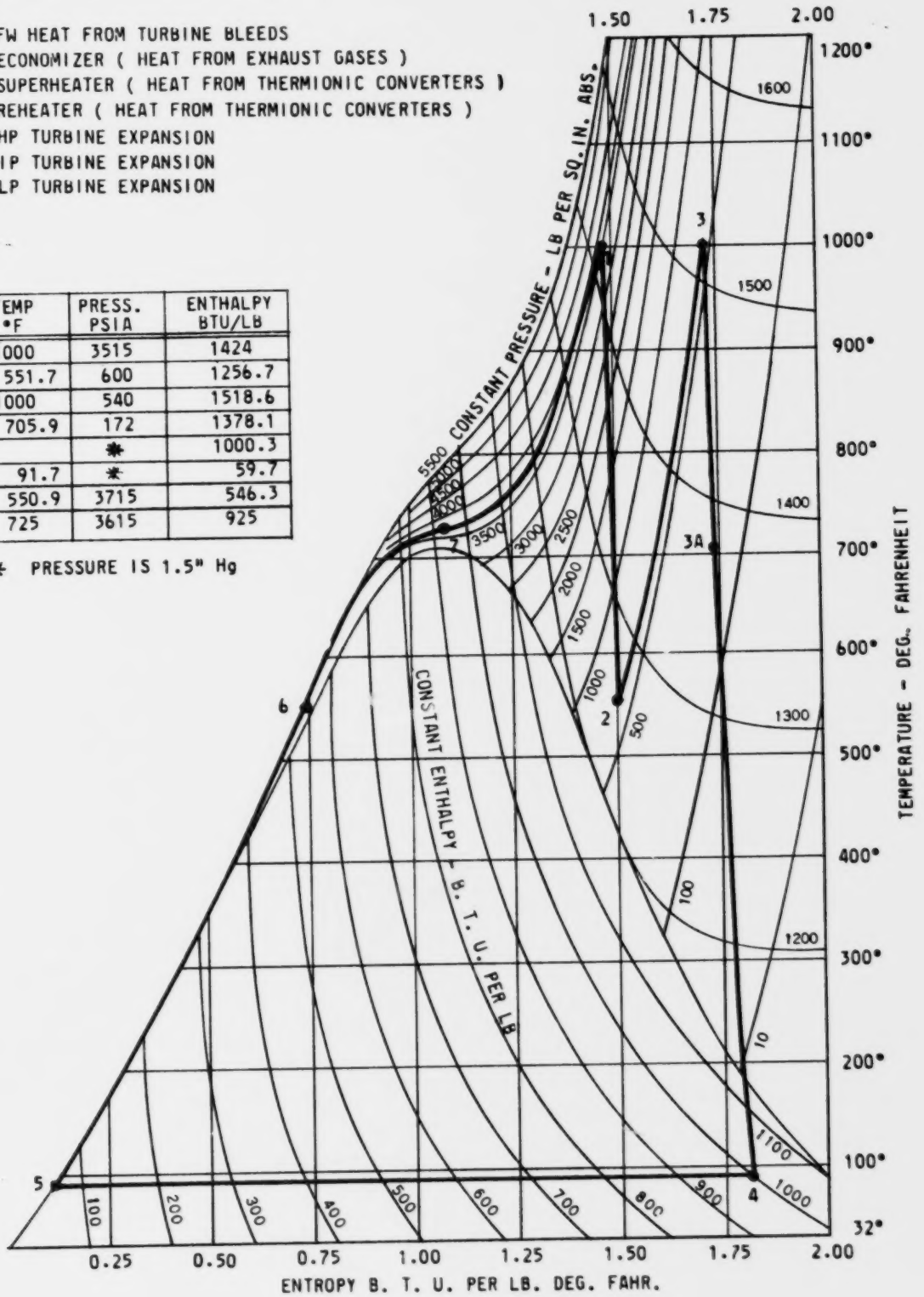


FIGURE 8

T. V. A. BULL RUN TEMPERATURE - ENTROPY CHART (WITH TOPPING)

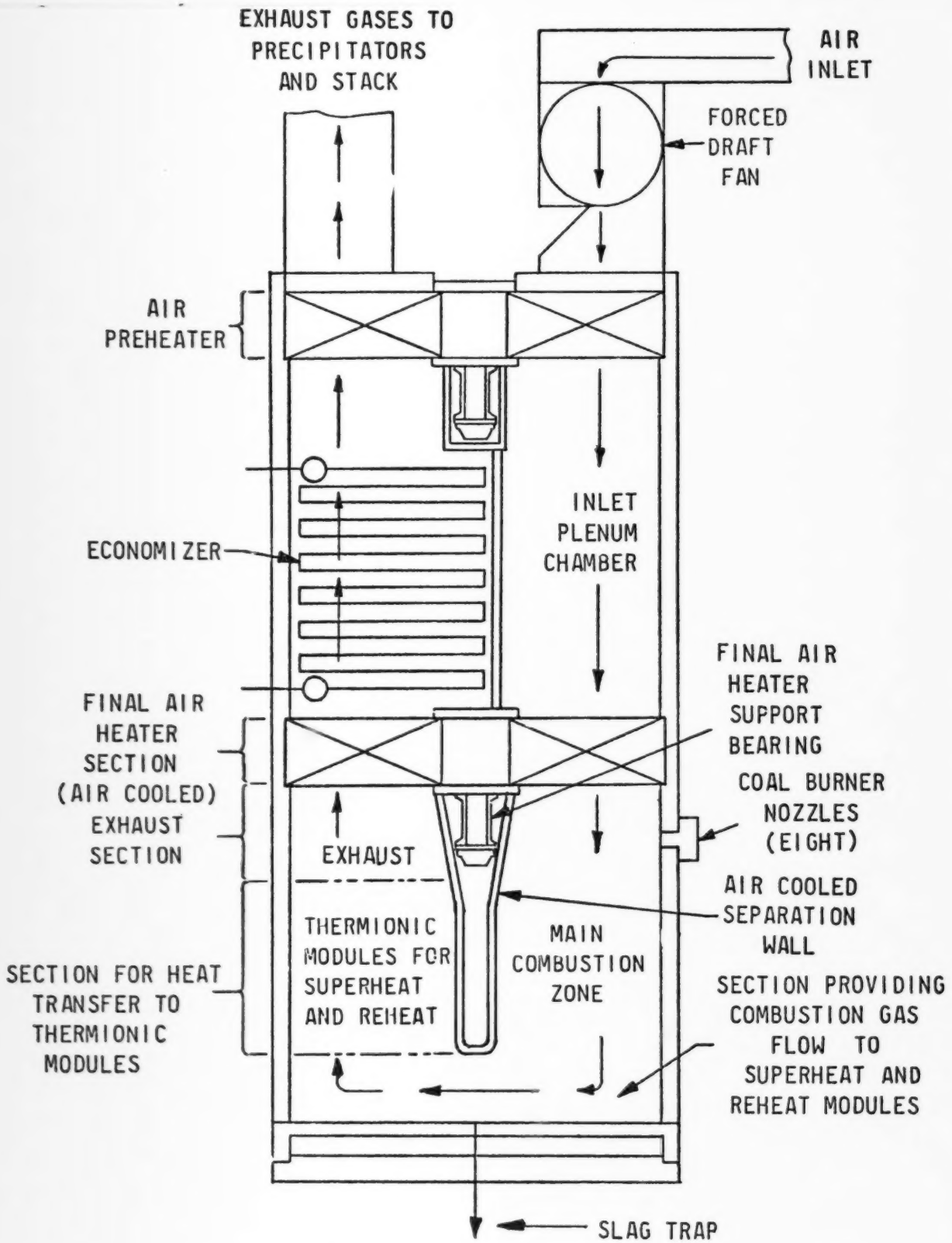


FIGURE 9
THERMIONIC FURNACE MODULE

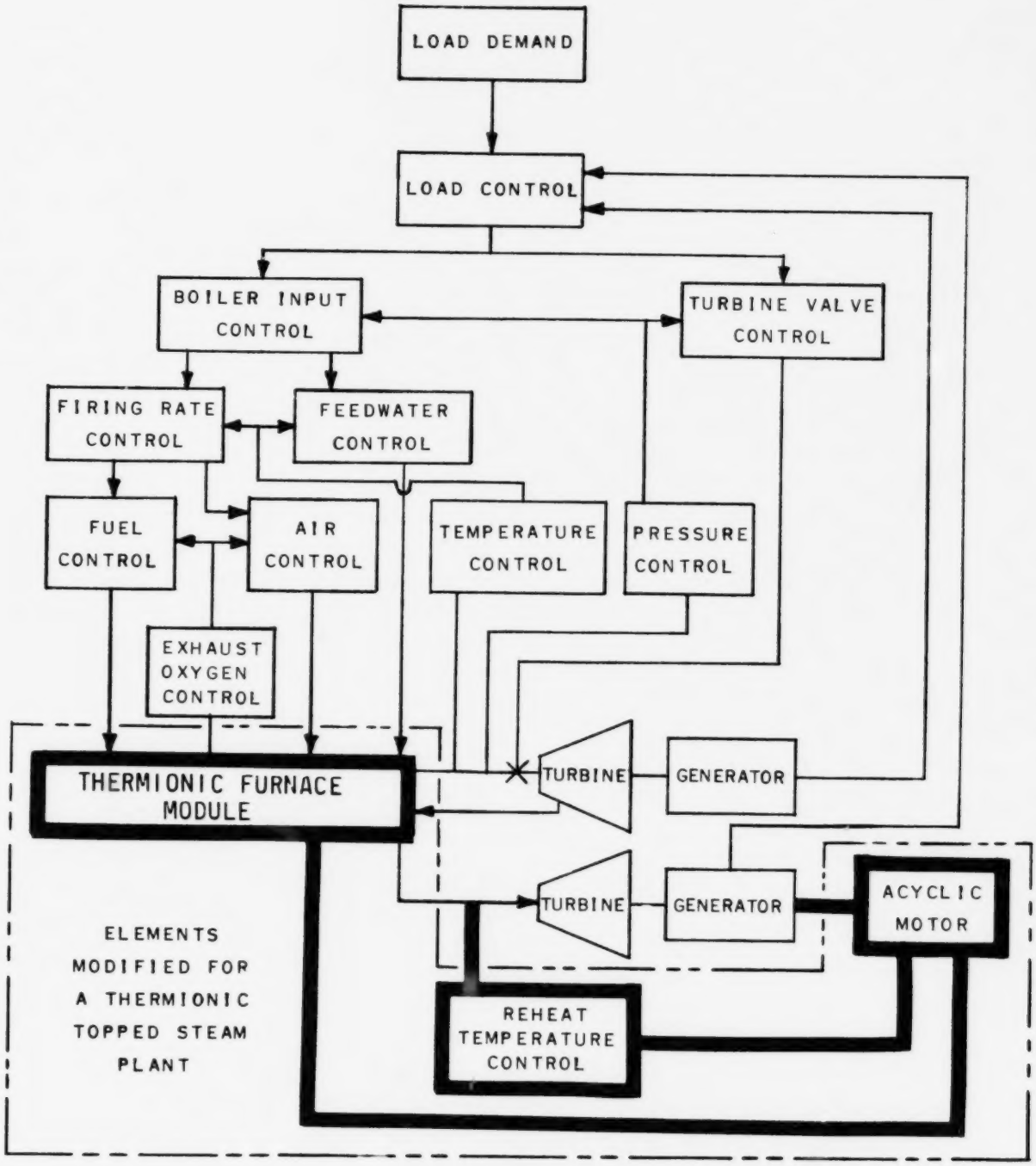


FIGURE 10

COMBUSTION CONTROL SYSTEM SCHEMATIC

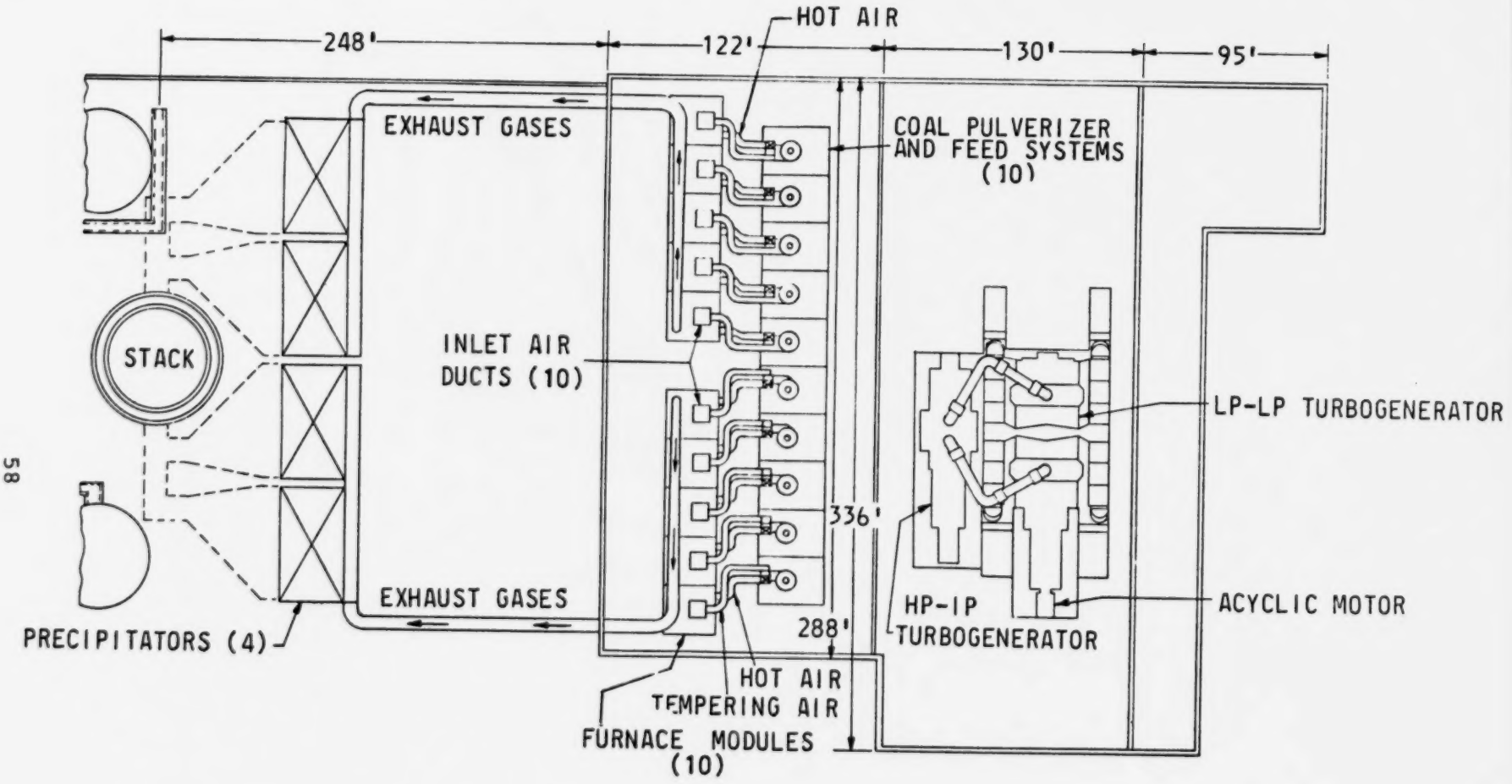


FIGURE 11
PLAN VIEW; T.V.A. BULL RUN WITH THERMIONIC TOPPING

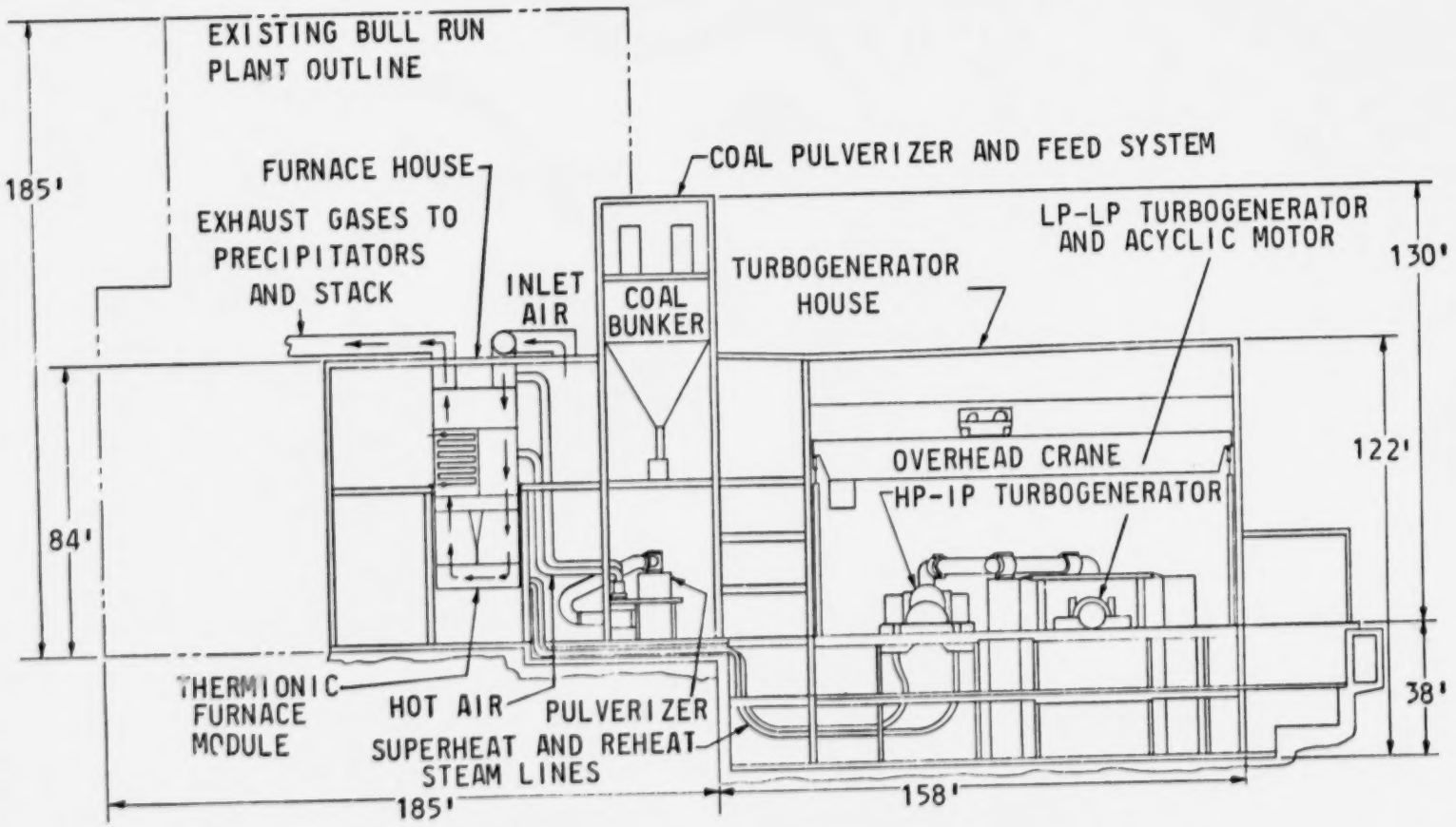


FIGURE 12
ELEVATION VIEW; T.V.A. BULL RUN WITH THERMIONIC TOPPING

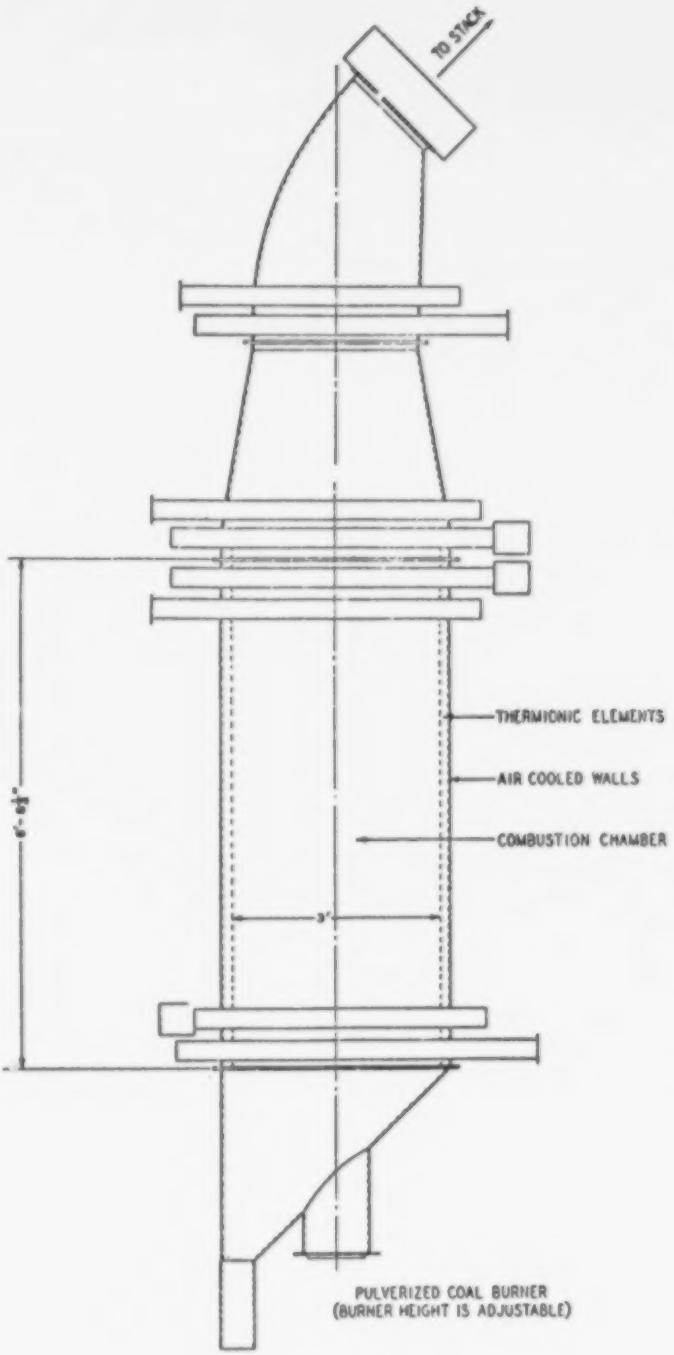


FIGURE 13

COMBUSTION ENGINEERING TEST FURNACE

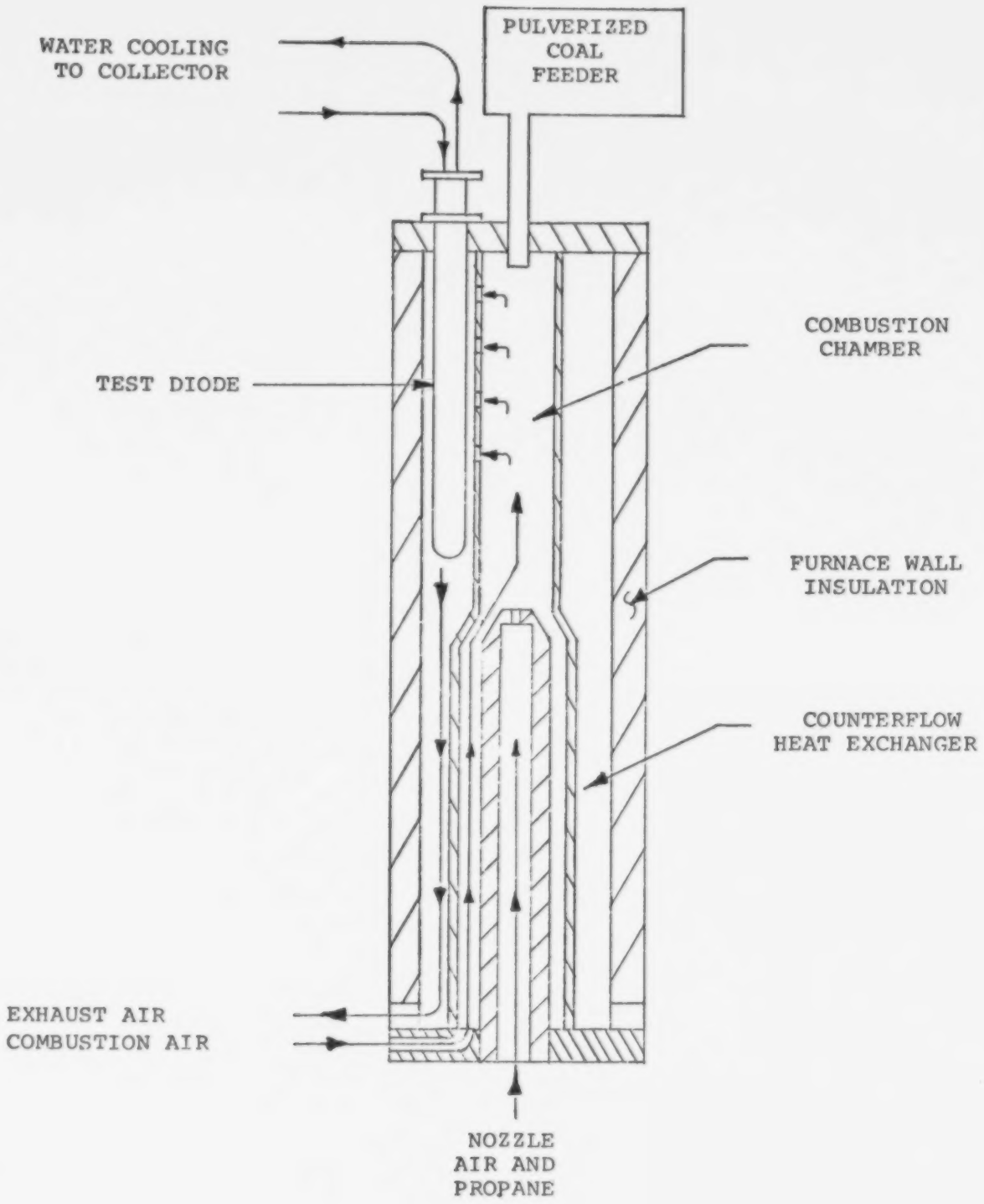


FIGURE 14

CONVERTER TEST FURNACE
WITH COAL AND/OR PROPANE FUEL

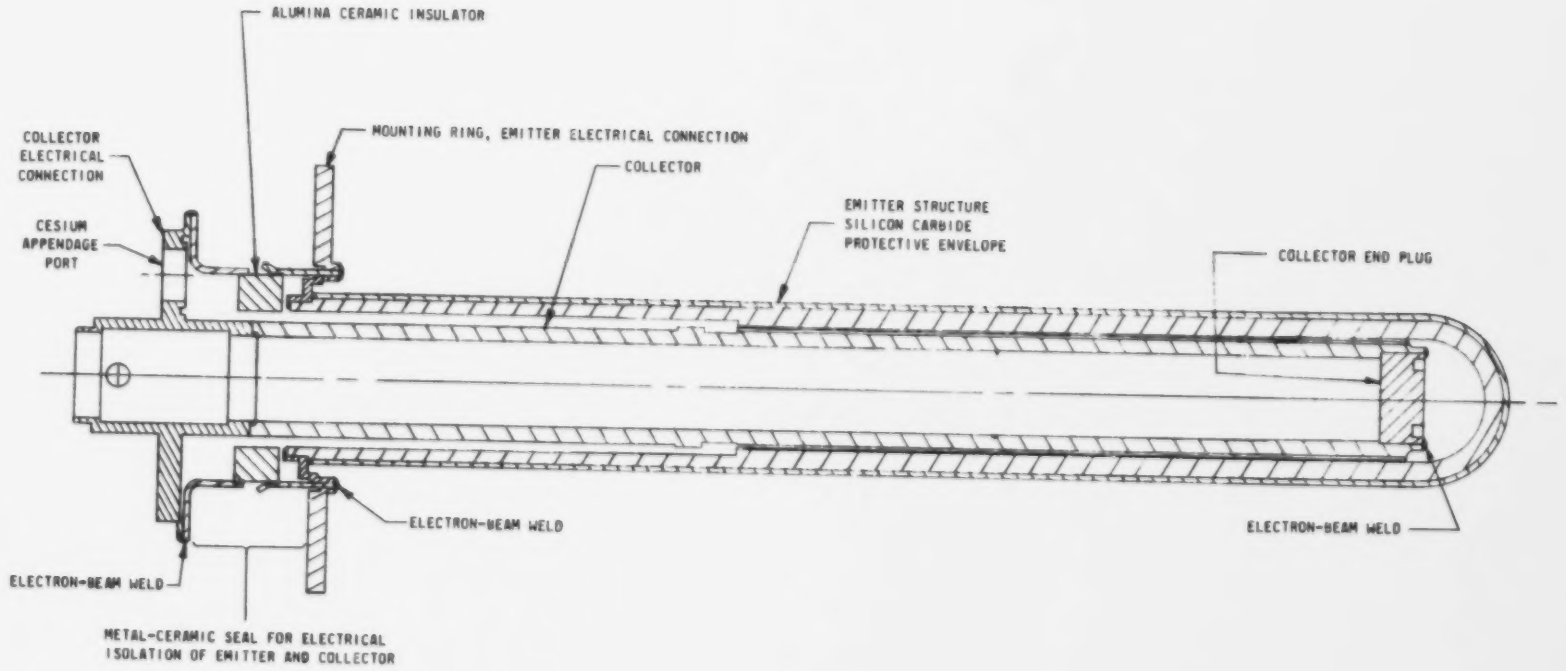


FIGURE 15
THERMIONIC CONVERTER
TEST DESIGN ASSEMBLY

FIGURE 16

EMITTER FROM CONVERTER NO. 492.
FAILURE AREA SHOWS ENVELOPE CHIP
MISSING, UNDERLYING TUNGSTIC OXIDE.

FIGURE 17

CONVERTER NO. 489, ENVELOPE CROSS-SECTION
AT 1" FROM (HOT) NOSE END.
MAGNIFICATION 100X, AS POLISHED.

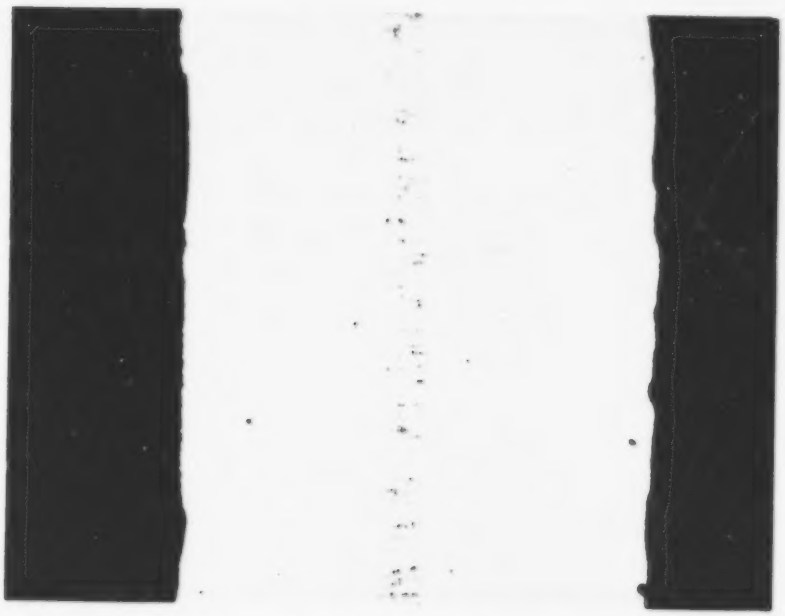


FIGURE 18

CONVERTER NO. 489, ENVELOPE CROSS-SECTION
AT 2" FROM (HOT) NOSE END.
MAGNIFICATION 100X AS POLISHED.

FIGURE 19

CONVERTER NO. 489, ENVELOPE CROSS-SECTION
AT 3" FROM (HOT) NOSE END.
MAGNIFICATION 100X AS POLISHED.

FIGURE 20

CONVERTER NO. 489, ENVELOPE CROSS-SECTION
AT 4" FROM (HOT) NOSE END.
MAGNIFICATION 100X AS POLISHED.

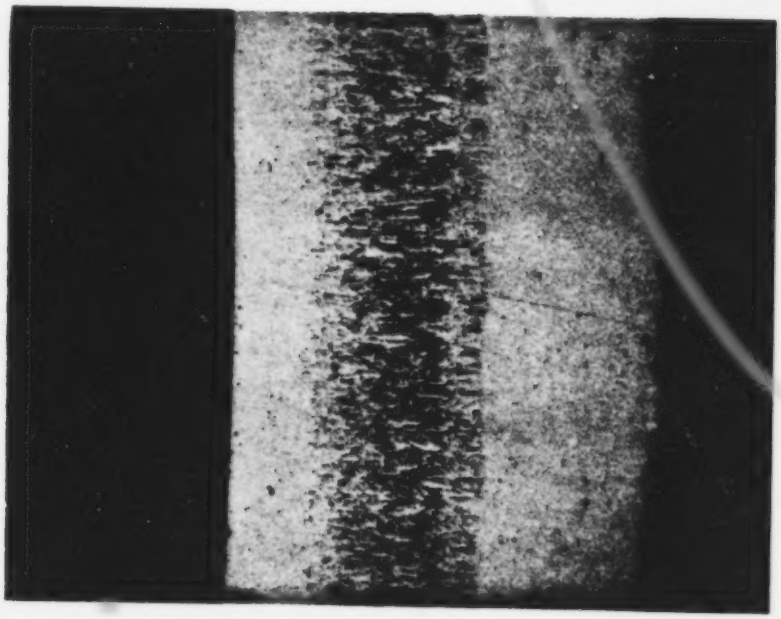


FIGURE 21

CONVERTER NO. 489, ENVELOPE CROSS-SECTION
AT 5" FROM (HOT) NOSE END.
MAGNIFICATION 100X AS POLISHED.

FIGURE 22

CONVERTER NO. 490, ENVELOPE CROSS-SECTION
AT 2" FROM (HOT) NOSE END.
MAGNIFICATION 100X AS POLISHED.

FIGURE 23

CONVERTER NO. 490, ENVELOPE CROSS-SECTION
AT 3" FROM (HOT) NOSE END.
MAGNIFICATION 100X AS POLISHED.

FIGURE 24

CONVERTER NO. 490, ENVELOPE CROSS-SECTION
AT 4" FROM (HOT) NOSE END.
MAGNIFICATION 100X AS POLISHED.

FIGURE 25

CONVERTER NO. 490, ENVELOPE CROSS-SECTION
AT 5" FROM (HOT) NOSE END.
MAGNIFICATION 100X AS POLISHED.

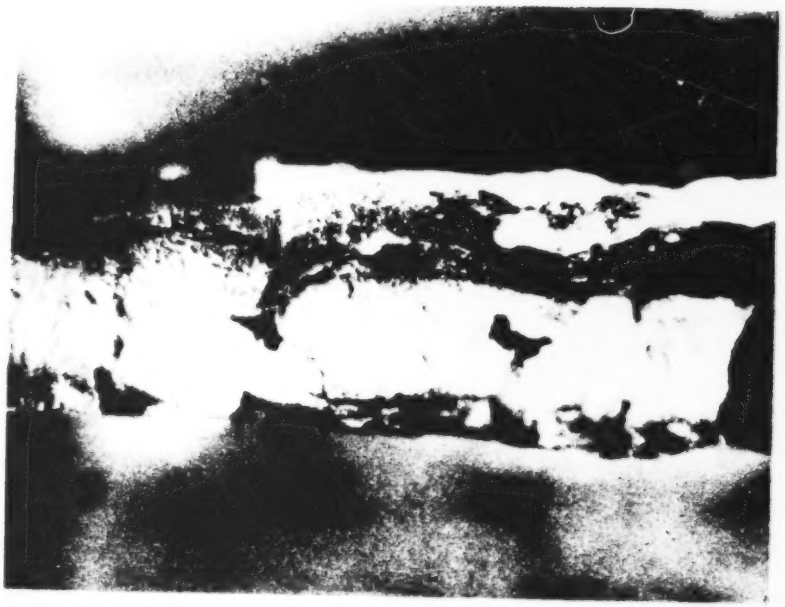


FIGURE 26
CONVERTER NO. 490, EDGE VIEW OF CHIP FROM ENVELOPE FAILURE REGION OF DIODE.
MAGNIFICATION 32X

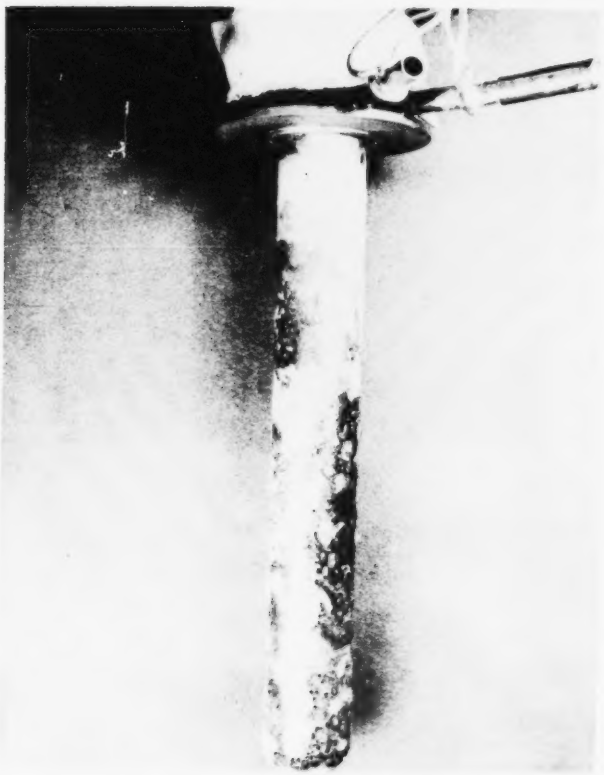


FIGURE 27

CONVERTER NO. 495 AFTER SIX HOURS
IN COAL-FIRED FURNACE

FIGURE 28

CONVERTER NO. 498 AFTER 85 HOURS OF OPERATION, WITH SLAG COATING FROM COAL FIRING

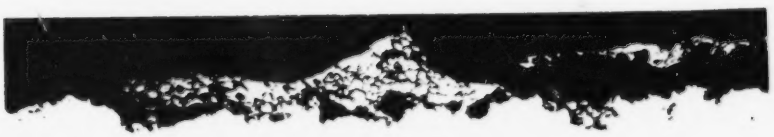


FIGURE 29

SECTION OF CONVERTER NO. 498 SILICON CARBIDE ENVELOPE (BRIGHT AREA) WITH (GRAY) SLAG COATING.
MAGNIFICATION 100X AS POLISHED.

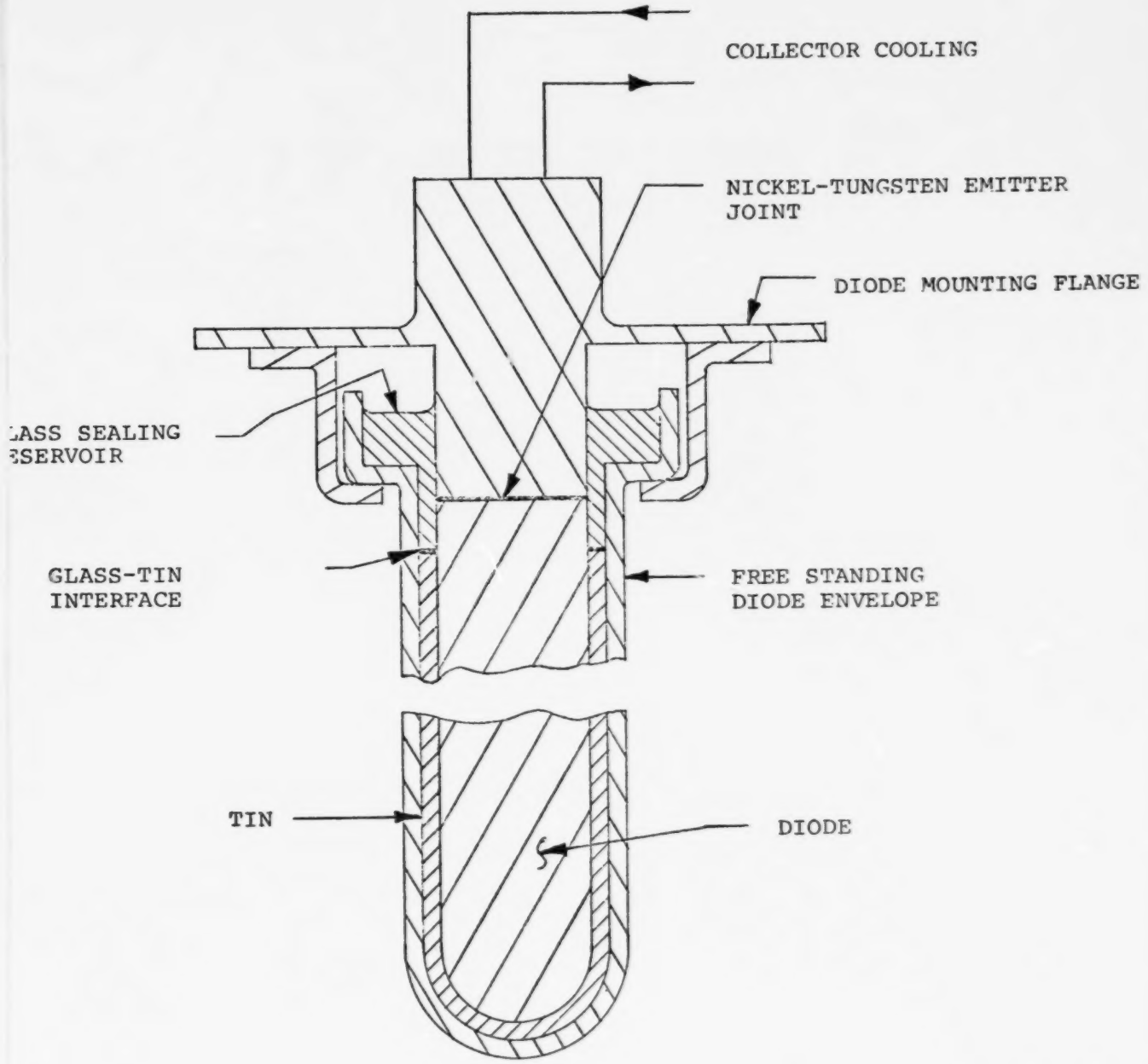


FIGURE 30

SCHEMATIC OF CONVERTER WITH FREE STANDING ENVELOPE

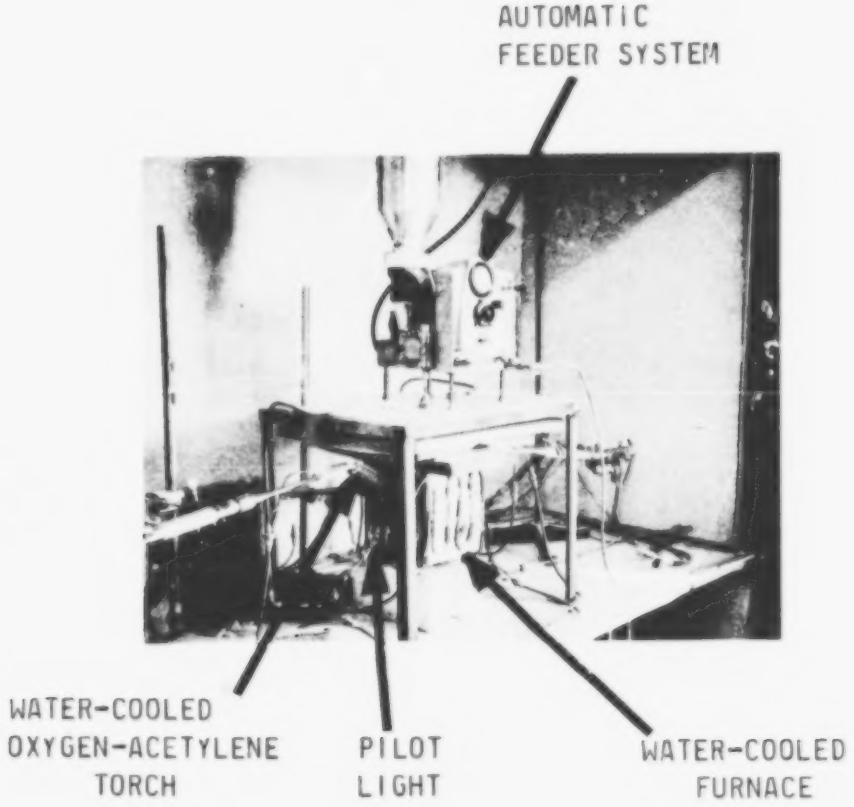


FIGURE 31

TEMPERATURE TEST FACILITY WITH
AUTOMATIC FEEDER SYSTEM

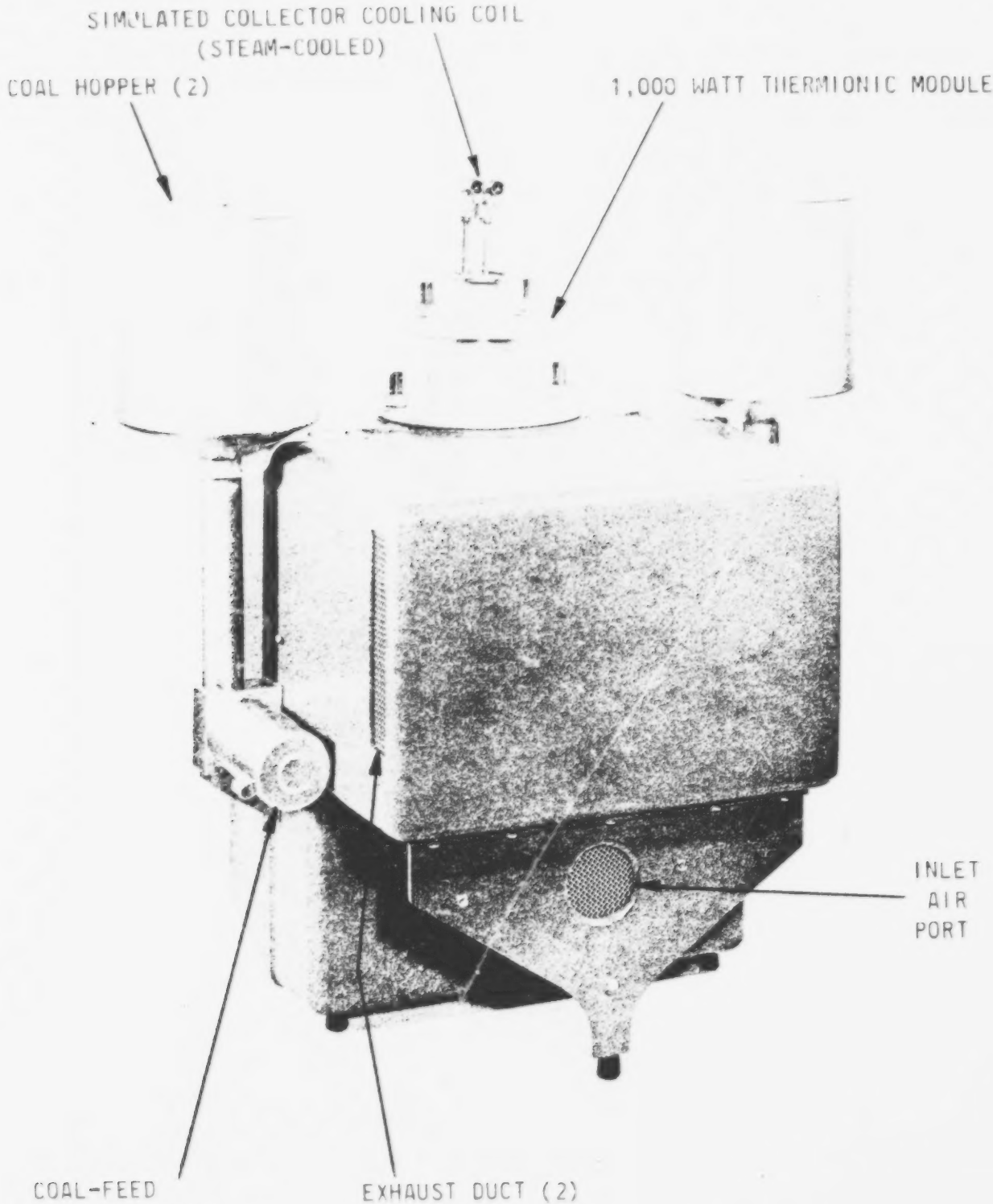


FIGURE 32

1,000 WATT THERMIONIC MODULE AND COAL-FIRED FURNACE
(CLOSED VIEW)

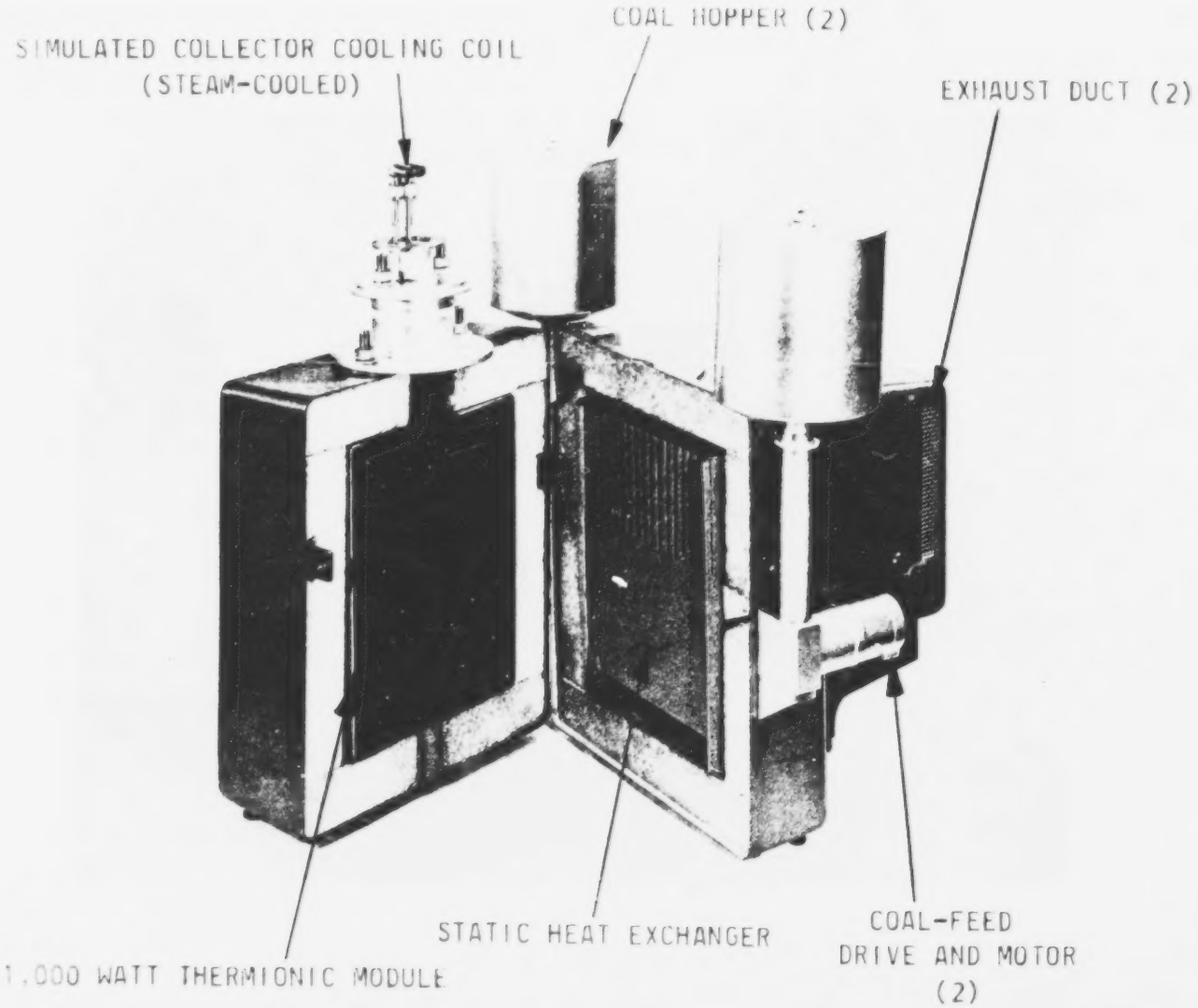


FIGURE 33

1,000 WATT THERMIONIC MODULE AND COAL-FIRED FURNACE
(OPEN VIEW)

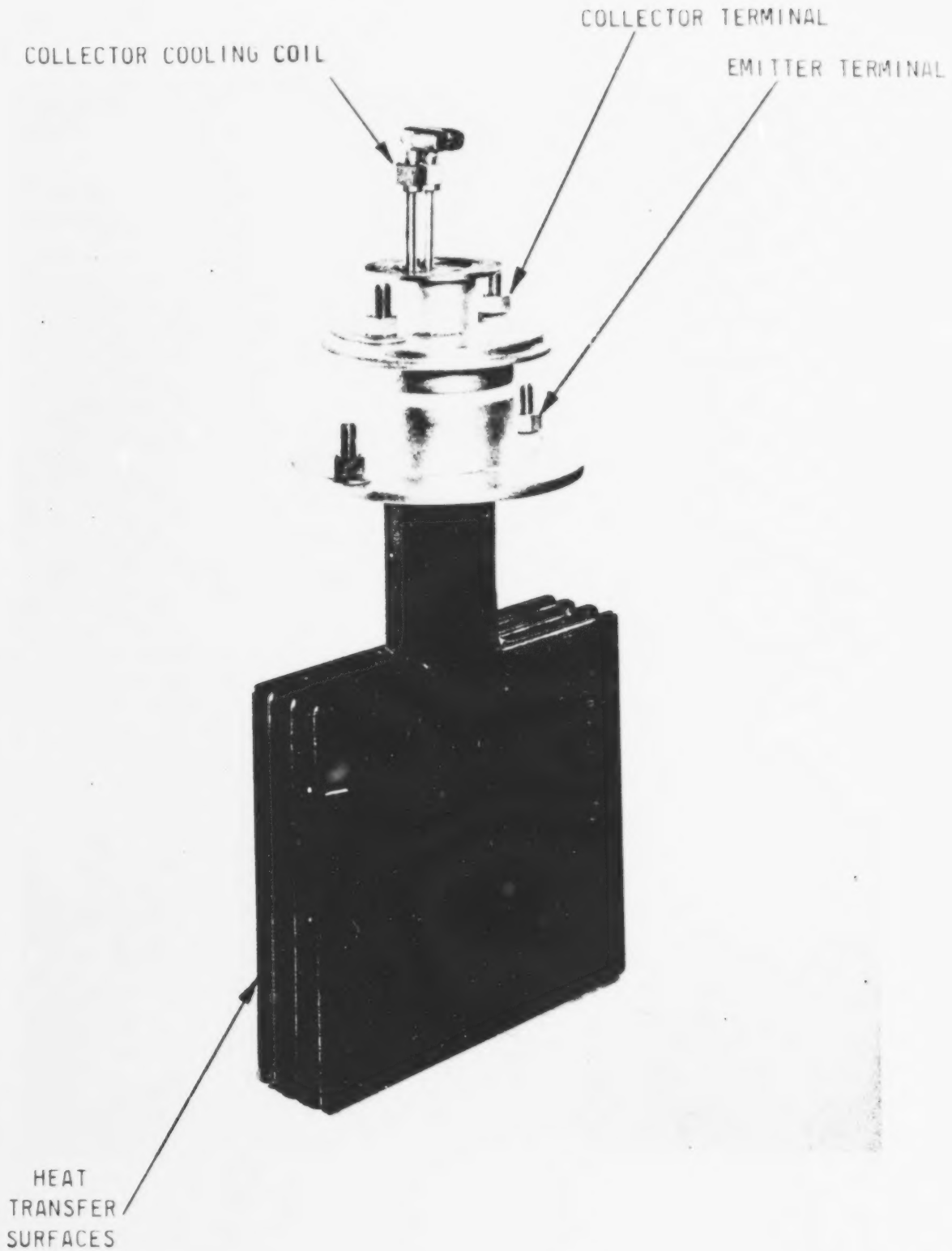


FIGURE 34

1,000 WATT THERMIONIC MODULE ASSEMBLY

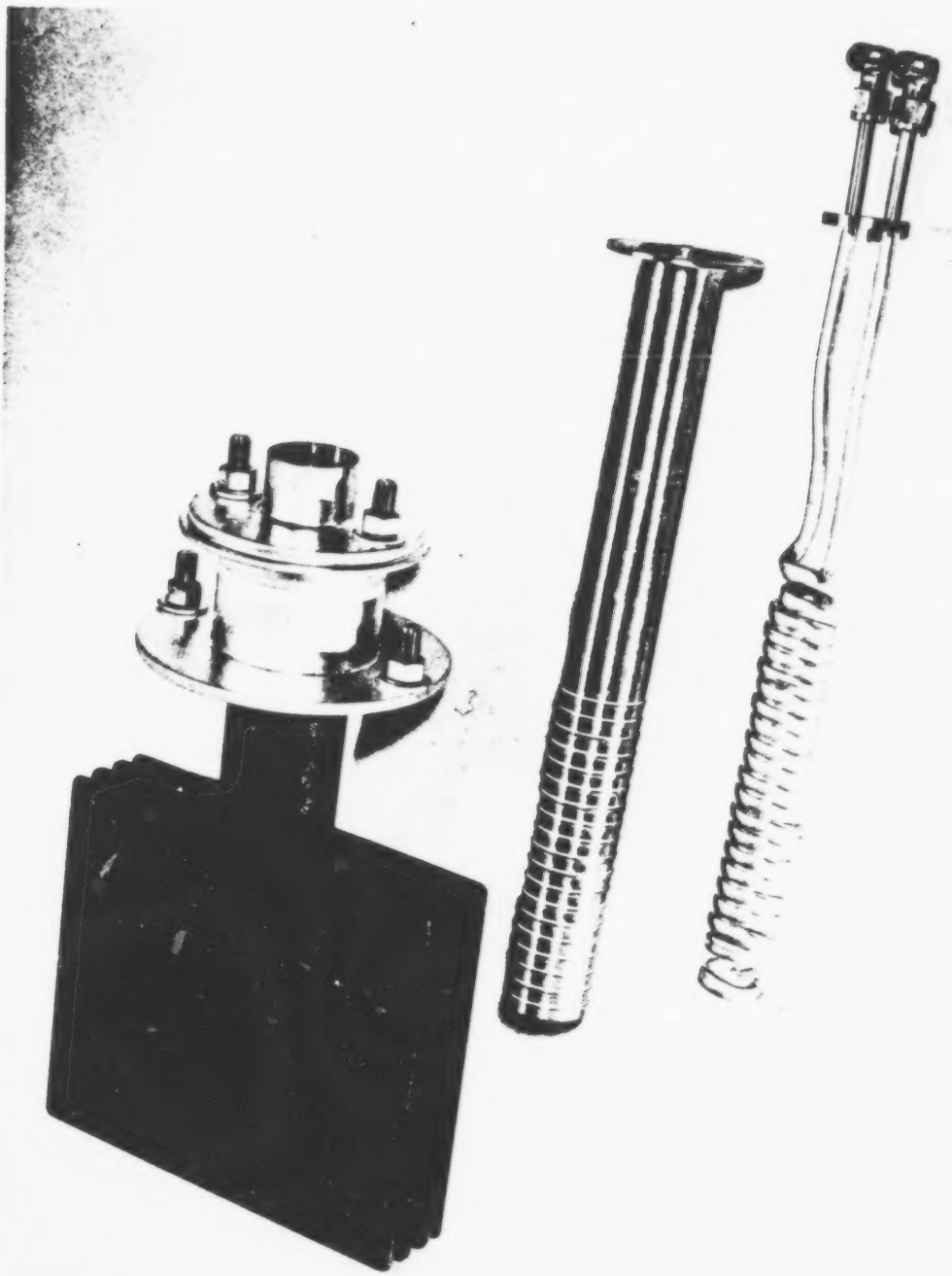


FIGURE 35

1,000 WATT THERMIONIC MODULE COMPONENTS

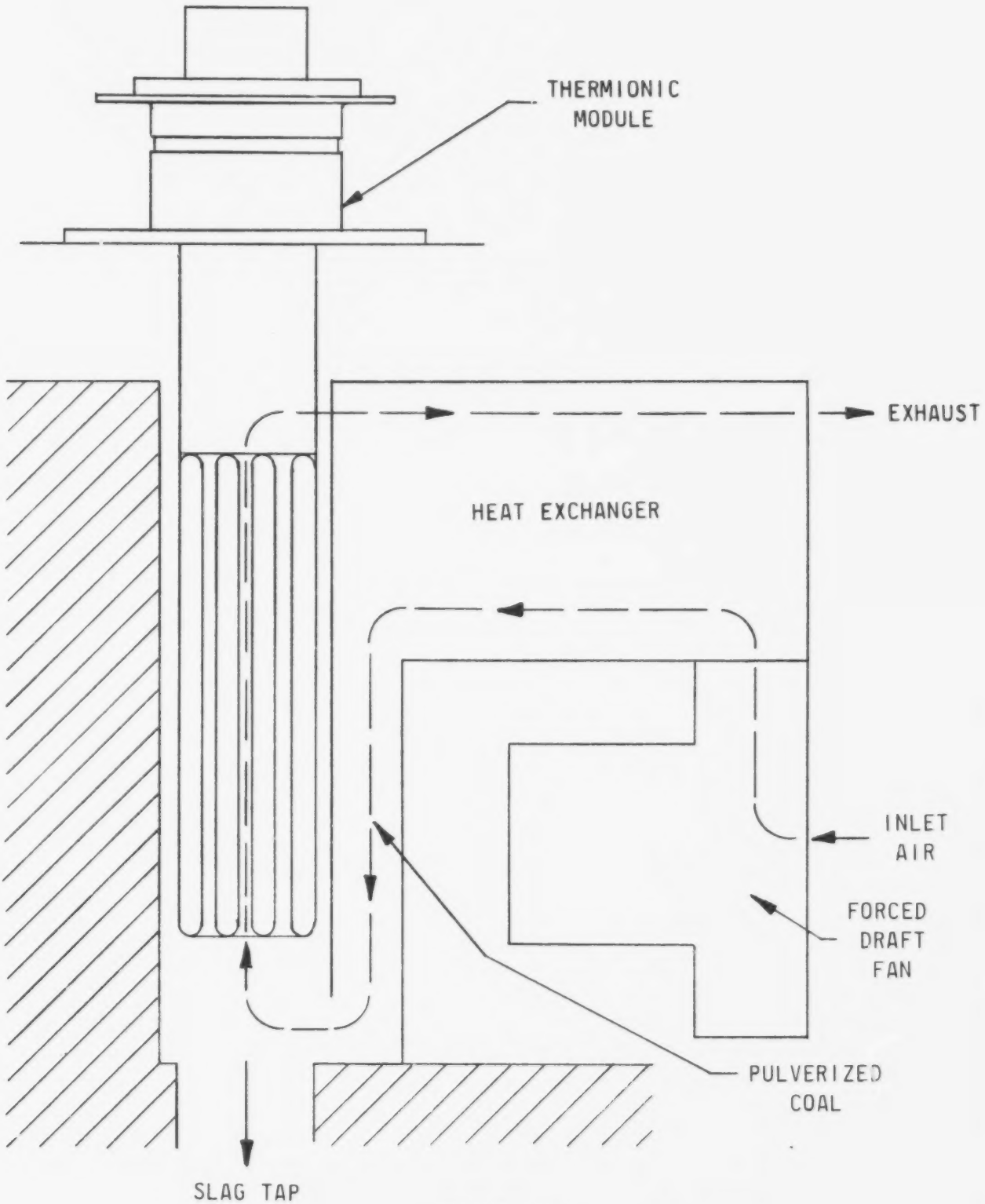


FIGURE 36

COAL-FIRED FURNACE SCHEMATIC

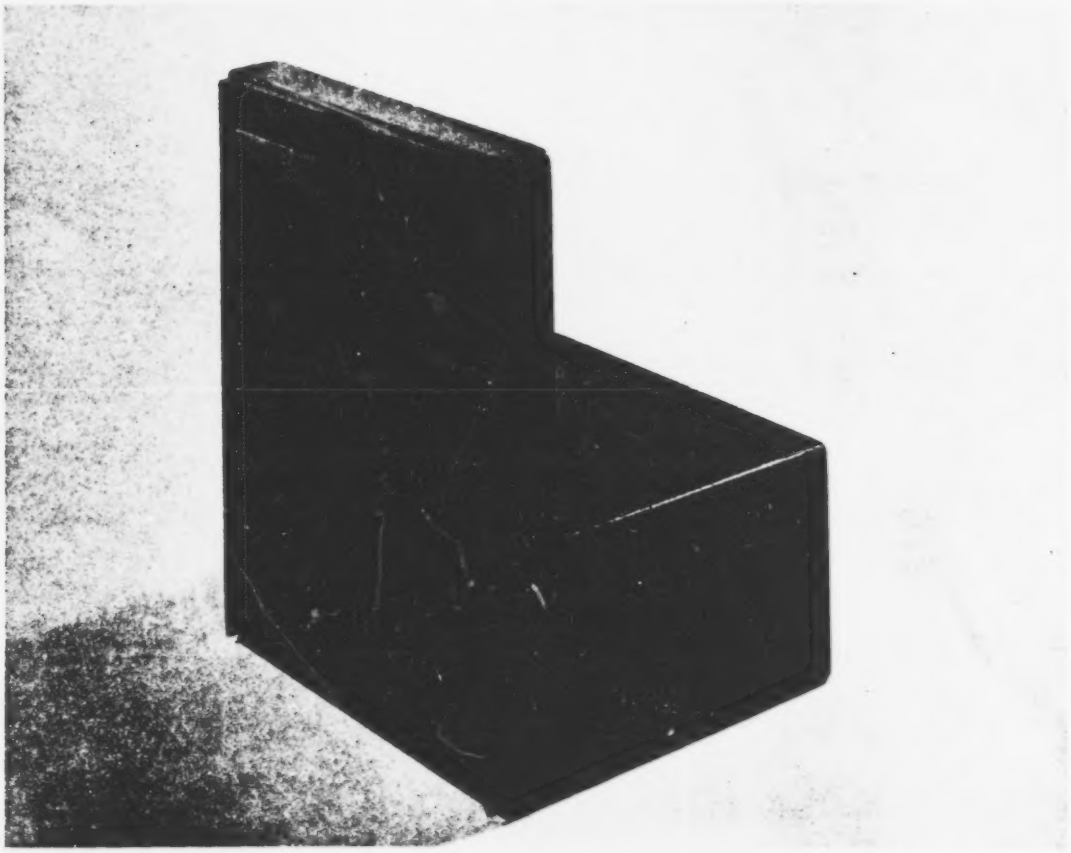


FIGURE 37

STATIC HEAT EXCHANGER FOR COAL-FIRED FURNACE

Final Report - Supplement

THERMIONIC TOPPING CONVERTER FOR A COAL-FIRED POWER PLANT

Prepared for:

OFFICE OF COAL RESEARCH
DEPARTMENT OF THE INTERIOR
WASHINGTON, D.C. 20240

CONTRACT 14-01-0001-499

By: ANTHONY J. CASSANO
JOHN R. BEDELL

CCC Project 60-6445

CCC Report 60-6445-18

Approved: RICHARD E. ENGDAHL, MANAGER
Advanced Research and Development

FOREWORD

This report is presented as addendum to CCC Report 60-6445-17 under Contract 14-01-0001-499, conducted by Consolidated Controls Corporation, under sponsorship by the Office of Coal Research, U. S. Department of the Interior. Mr. G. I. Staber, Assistant Chief of the Utilization Division, was project monitor for the Office of Coal Research.

Project supervision was by R. E. Engdahl, Manager of Advanced Research and Development. Principal investigators were A. J. Cassano, Research Physicist and J. R. Bedell, Techniques Manager.

Energy Research Corporation has been formed to carry forward the work of Consolidated Controls Corporation in the area of energy conversion. Project supervision, principal investigators, staff and facilities have remained unchanged.

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1.0 SUMMARY

Materials problems, specifically in the protective envelopes for the diodes of the thermionic topping system, were encountered and described in prior report CCC-6445-17. This report is presented as addendum thereto, describing the work performed to resolve these problems.

Diode development efforts encompassed the endurance testing of diodes, the further investigation of silicon carbide synthesis parameters, and implementation of improved fabrication techniques and treatments suggested by the investigation results. Assembly design changes were also made to accommodate certain alternative materials processing modifications.

A primary aim of improved synthesis techniques was better structural uniformity along the entire axial length of protective silicon carbide envelopes. This goal was sccured by modifying the distribution and direction of flow of the synthesis gases during chemical vapor deposition of the silicon carbide envelopes. By controlling the gas flow, it was also possible to modify the deposition rate at different regions of the envelopes, thereby controlling thickness as well as structure.

This improvement in synthesis technique contributed to solution of the cold end failures occurring during diode tests. The high level of structural uniformity eliminated the previous tendency for free carbon to form within the envelope at the "open" end. With this improvement, diode lifetimes moved up to about 400 hours, and failures shifted from the cold end to the hot zone of the envelope.

The achievement of 400 hours lifetime has been no end in itself, but merely indicates solution of certain major materials problems. Work is now in progress to provide unstressed envelopes. These modifications should enable us to realize the potential indicated in the material improvements which have been made.

2.0 MATERIAL PROPERTY STUDIES

In order to tailor properly the assembled diode materials to their combined properties, it has been essential that these properties be accurately defined. With regard to protective coating of diode emitters, the thermal expansions of envelopes and emitters must be matched closely.

Although there have been data published for the thermal expansions of sintered silicon carbide and tungsten, we have felt that chemical vapor deposited silicon carbide, produced under the unique synthesis conditions in our laboratory, may not be represented by prior published data. The thermal expansion of our own CVD silicon carbide was therefore measured over the range of room temperature to about 2700°F. Other materials, such as CVD tungsten, sintered tungsten, molybdenum, and certain graphites were also similarly evaluated in the same equipment to provide comparative control data.

Table I is a descriptive presentation of the various specimens which had been subjected to thermal expansion testing and evaluation. Table II presents the derived linear coefficients of expansion, and Table III presents the $\Delta L/L$ values obtained from these specimens. A very significant revelation of this study was that the CVD silicon carbide expanded and contracted less than any of the forms of tungsten over the temperature intervals applied. These data contrasted with published data which had indicated sintered silicon carbide to have higher expansion coefficients than tungsten. Figure 1 contains plots of $\Delta L/L$ values for tungsten, silicon carbide and molybdenum, as published in Goldsmith et al (1), whereas Figure 2 presents corresponding plots from this study for CVD tungsten, CVD silicon carbide, and molybdenum (2). The differences are quite obvious, and are cited in the figures.

Flat coupons of CVD silicon carbide were subjected to bend testing, to determine maximum tensile strengths of the material. These specimens were ground and diamond polished to avoid stress riser effects of scratches and notches. The specimens were approximately 3/8" wide, .011" to .039" thick, and were bent between a span .730" long, as shown in Figures 3 and 4. Maximum tensile values well over 100,000 psi were determined by these tests, as recorded in Table IV. These high values, much higher than tensile figures generally obtained for sintered silicon carbide (6,000 - 10,000 psi), emphasize again the unique character of the chemical vapor deposited form of the material.

Additional physical testing of silicon carbide in the form of ring segments was also performed to determine residual stress effects, dimensional changes, and maximum failure stresses, as governed by certain synthesis conditions and post-synthesis heat treatments. Specimens were prepared according to Figure 5, and were tested to failure as shown in Figure 6. Test data and calculated values are presented in Table V. The maximum tensile stresses obtained for the segmented ring specimens, although much higher than for conventional silicon carbides, were considerably lower than values obtained in tests of the flat coupons. These lower values are presently attributed to the unpolished surface condition of the ring specimens, which were tested in the ground condition. It is felt that fewer and smaller stress concentrations will occur at a polished surface, resulting in higher test values.

3.0 PROCESSING AND DESIGN

Prior to securing the results of the thermal expansion tests, certain published data led us to assume that silicon carbide had a slightly higher coefficient of expansion than tungsten. In order to achieve a better expansion match, it was felt that alloying tungsten with molybdenum would provide us with substrate materials of higher expansion coefficients than pure tungsten, and thus more suitably matched to the CVD silicon carbide coatings. CVD tungsten - molybdenum emitter tubes, consisting of 25, 16, 10 and 5 weights percent molybdenum, alloyed with tungsten, were obtained and coated with silicon carbide. The newly formed carbide coatings consistently spalled in varying degrees from the tungsten molybdenum substrates, upon cooling from synthesis conditions to room temperature. Indications were that the carbide coatings were excessively compressed, owing to higher thermal contraction of the tungsten-molybdenum substrates during cooling. Shortly thereafter, the thermal expansion data were received, which confirmed the belief that mismatch between CVD silicon carbide and tungsten is actually aggravated by increasing the substrate expansion coefficient. It was apparent, after receipt of the thermal expansion test data, that 100% tungsten had the best thermal expansion match with the CVD silicon carbide coating.

Coatings of silicon carbide were thereafter deposited on 100% tungsten emitters, to produce what is designated as "integral" silicon carbide envelopes. To protect the region near the open end where the carbide terminated and where the tungsten was uncovered, a molten glass reservoir was introduced. This reservoir was maintained in a silicon carbide cup, conjoined with the envelope and tungsten emitter, as shown in Figure 7. The construction of this assembly was made possible by our development of a satisfactory brazing alloy which could provide the described joint between silicon carbide cup, silicon carbide envelope, and tungsten emitter body.

A promising alternative to the "integral" envelope design, in which mismatch is a problem, is a design using a free-standing protective envelope, which is not in contact with the tungsten emitter, but instead transmits heat across a molten tin-filled annulus. By this design, very large differences in expansion coefficients can exist between envelopes and emitters. A major problem which does arise, however, is the metal-ceramic seal necessary to permit complete closure by the envelope. Brazing alloys

and procedures, to join silicon carbide to metallic members, have been developed and are being used to produce free-standing envelopes for diodes. Further effort is necessary, however, to complete the assembly procedure.

The proper processing of free-standing silicon carbide included post-synthesis heat treatment, to relieve residual stresses incurring during fabrication. This treatment was developed as part of our effort to produce improved silicon carbide. Table V, which contains data on cylindrical test specimens, reveals the effects of heat treatment upon residual stress: Diameter represents the change in diameter each specimen experiences after slotting it, as shown in Figure 5. After heat treatment there are no diameter changes, which indicate a significant reduction in residual stresses through heat treatment. Unfortunately, we have been unable to apply the treatment to those silicon carbide coatings which have been integrally deposited on tungsten, as the treatment induces some reaction between the carbide and the tungsten substrate.

4.0 DIODE TESTING

Progressive testing of twelve diode assemblies, from August 1968 through September 1969, is represented in Table VI. Where a diode failure occurred, it usually resulted from breach of the protective carbide envelope. Protective envelopes have remained the prime target for technical improvement. It can be seen that the last few diodes increased in lifetime to approximately 400 hours. It is also apparent that the higher lifetimes coincided with a change in failure location. Whereas short-lived envelopes generally failed near the cold, "open" end, the longer lived envelopes failed in the hot zone, near or at the "closed" end.

Two major modifications were responsible for the increase in lifetime. The first of these has been our development of improved silicon carbide synthesis techniques. We succeeded in synthesizing silicon carbide envelopes which were uniform in structure along their entire axial lengths. This achievement enabled us to rid ourselves of free carbon in the envelopes near the "open" ends without producing free silicon near the "closed" ends. By eliminating free carbon, atmospheric penetration, via free carbon in the envelope structure, was prevented. Failure by atmospheric attack through the shell at the cold end was thus avoided.

The second modification which helped prevent "cold" end failures, was a fluid glass seal, which provided an impermeable cover for the transition zone where the silicon carbide envelope terminated and a nickel member began. These latter seals were used in tests 507, 508, 509, and 510. The failure of 507 is discounted, as failure was not in the envelope, but instead at the collector, near a weld. Test 508 lasted for 406 hours, a considerable increase over the other runs, and test 509 endured for 385 hours. Test 510 was not run to destruction, and is still intact. It appears significant that the combination of improved synthesis technique and use of a fluid glass seal only occurred in these last four diodes, and we feel that improved performance was the direct result.

Envelope failures in the hot zone suggested that some dimensional change of the envelopes occurred with time-at-temperature. It is believed that residual stresses, in process of slowly being relieved at operating temperature, were responsible for slight dimensional changes. Since the envelopes were integrally bonded to the tungsten substrates, these dimensional changes focussed stresses at the failure locations.

5.0 PROJECTED EFFORT

Residual stresses, which we have observed in free-standing CVD silicon carbide tubes, have been relieved by heat treatment. This heat treatment is sufficient to induce some reaction between tungsten and silicon carbide, and, therefore, has only been successfully used on free-standing carbide envelopes.

Future efforts shall be directed toward construction of diodes with free-standing, stress relieved, carbide envelopes. These efforts shall include development of techniques for providing permanent high temperature seals between silicon carbide envelopes and metallic elements of the assembly.

Efforts shall also be directed toward developing techniques for stress relieving an integral silicon carbide coating without causing reaction with the tungsten emitter.

6.0 REFERENCES

1. Goldsmith, Waterman and Hirschhorn, " Handbook of Thermophysical Properties of Solid Materials ", Macmillan, V. 1, pp. 423, 424, 685, 686; V. 3, pp. 423, 424, (1961).

2. Dynatech Report CCS-1, to Consolidated Controls Corporation, on The Linear Coefficient of Expansion of Ten Materials, Unpublished Data, 1969.

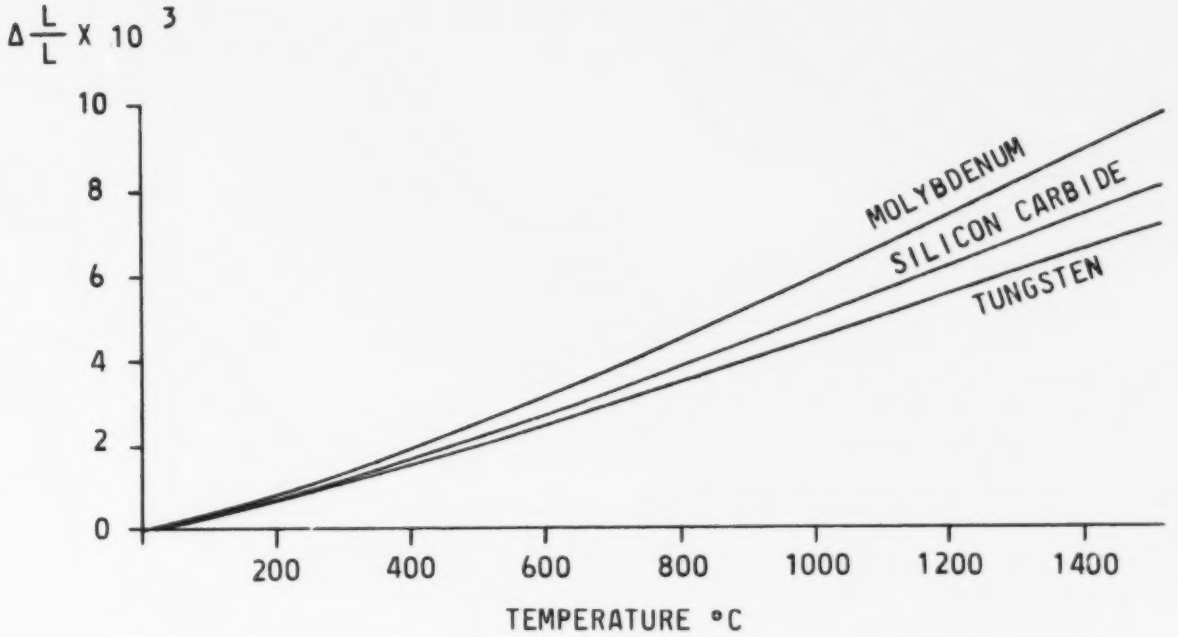

Figure 1: Linear Thermal Expansions, plotted from Goldsmith[1]. Note that a higher thermal expansion is indicated for silicon carbide than for tungsten.

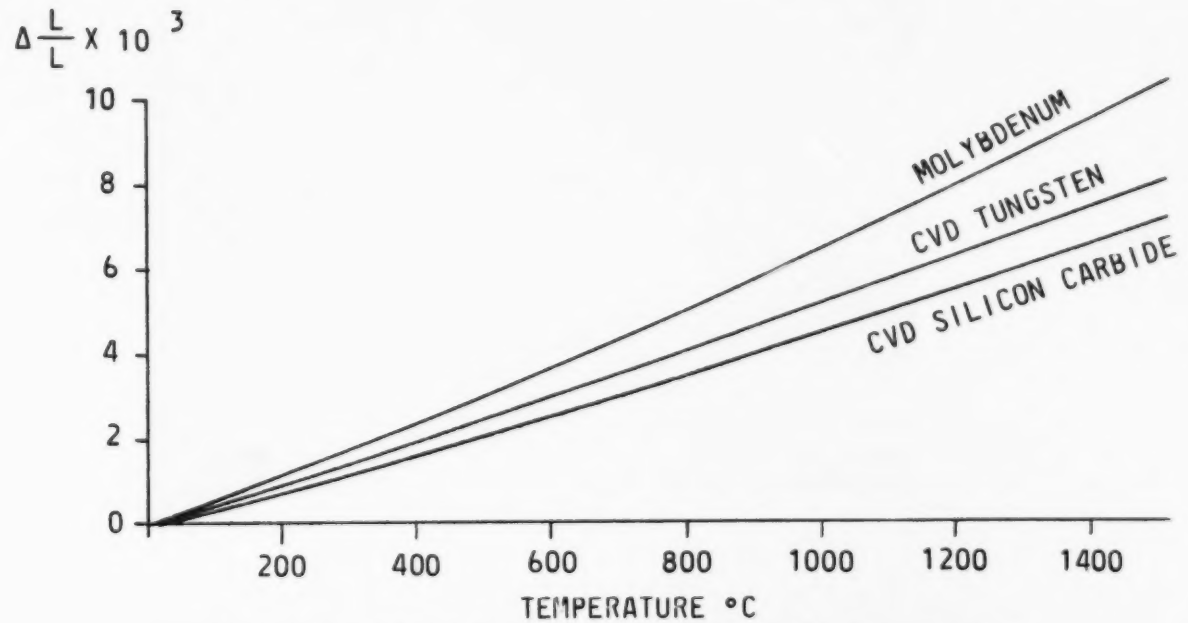

Figure 2: Linear Thermal Expansions, plotted from data with our own materials[2]. Note that a higher thermal expansion is indicated for CVD tungsten than for CVD silicon carbide.

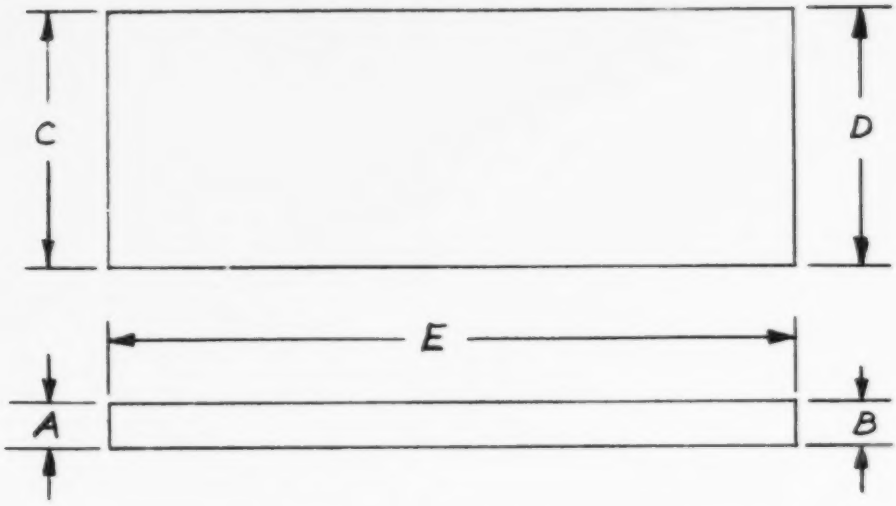

Figure 3: Bend Test Coupon, dimensions referenced alphabetically to those of Table IV.

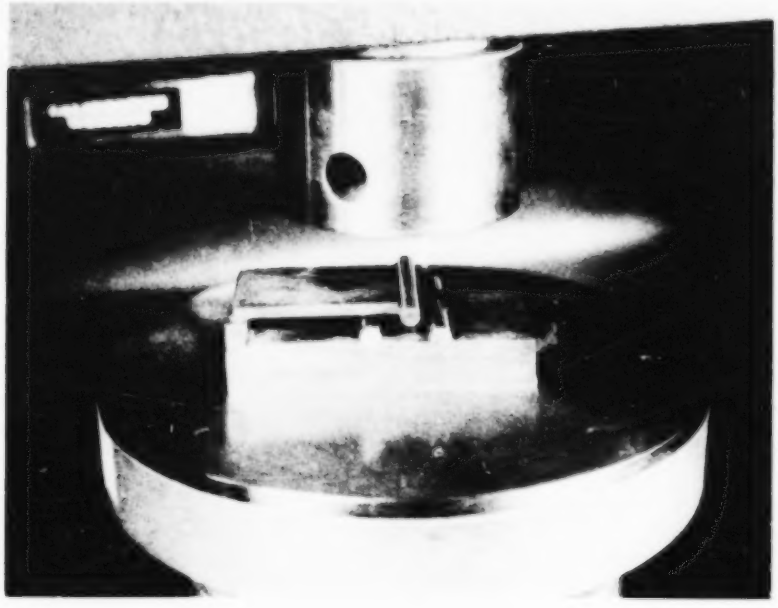

Figure 4: Bend Test. Specimen is deflected to failure between two fixed 1/4" steel rods by a third 1/4" steel rod. Third rod is free to move vertically, but is maintained at a midway position between the supporting rods.

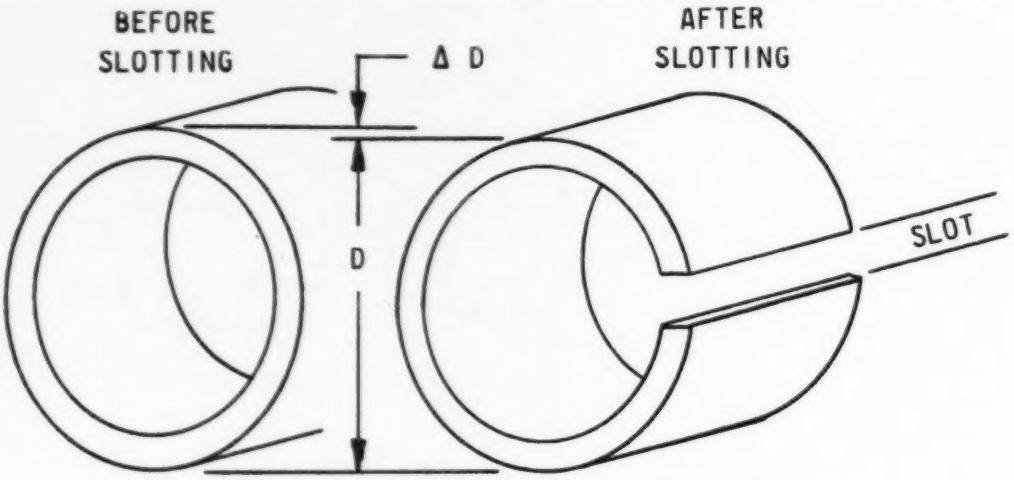

Figure 5: Ring Test Specimen, before and after slotting. A change in diameter is indicative of prior residual stresses.

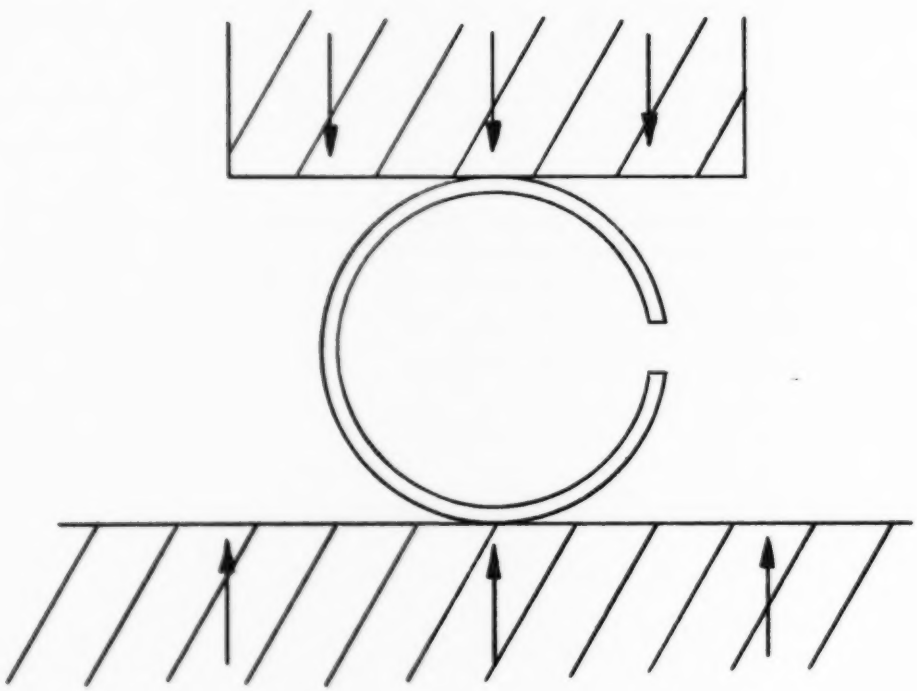

Figure 6: Ring Test. Specimen is deflected to failure between platens of testing machine.

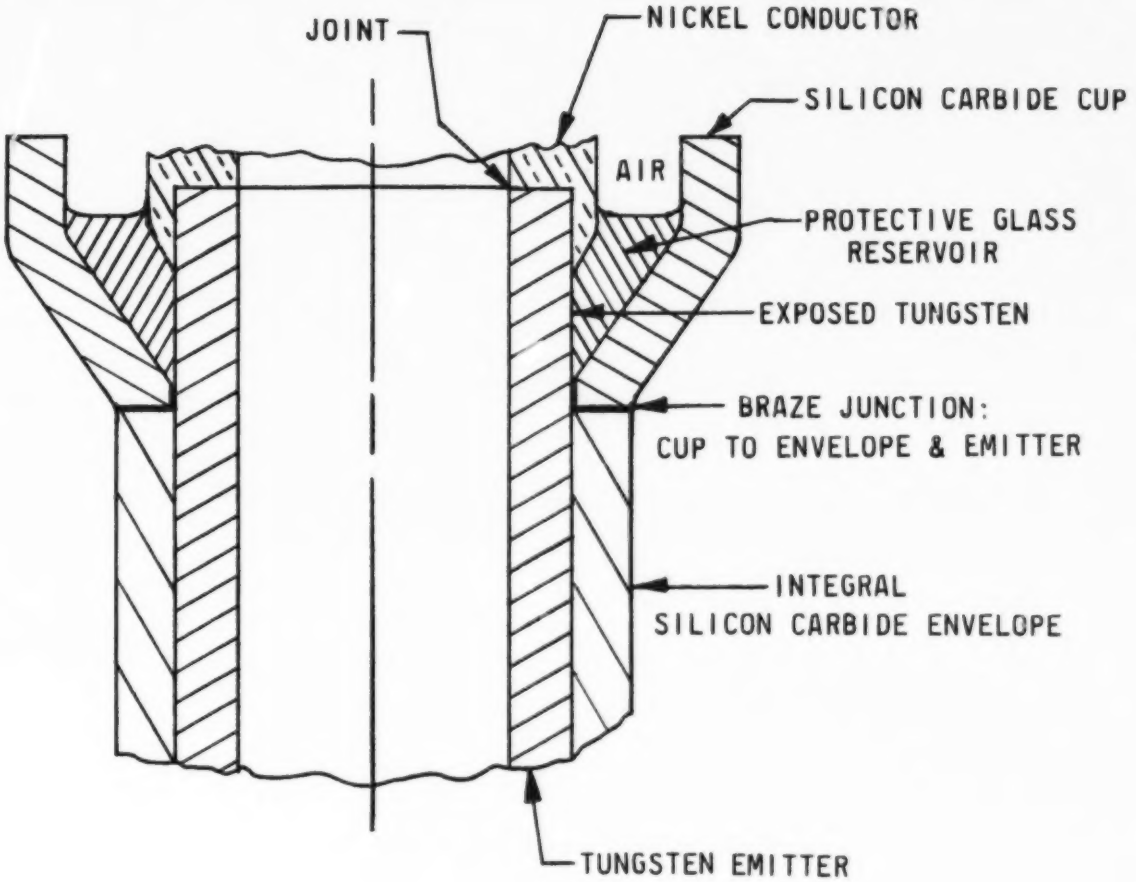

Figure 7: Protected Joint. Molten glass reservoir serves to protect uncoated portion of tungsten, between silicon carbide coating and nickel. Reservoir is contained in silicon carbide cup, which is brazed to tungsten and carbide coating.

TABLE I

DETAILS OF SAMPLES SUPPLIED FOR EXPANSION MEASUREMENTS

SAMPLE #	MATERIAL	DESIGNATION	APPROX. DIMENSIONS, mm	DETAILS OF TEST
1	Silicon Carbide	Nose A Longitudinal	47 x 4 x 1 rectangular bar cut parallel to axis of tube	Measurements on heating and cooling one cycle
2	Silicon Carbide	End C Longitudinal	47 x 4 x 1 rectangular bar cut parallel to axis to tube	Measurements on heating and cooling one cycle
3	Silicon Carbide	Nose B Transverse	12 x 5 x 1 crescent cut perpendicular to axis of tube	Measurements on heating and cooling one cycle
4	Silicon Carbide	Nose C Transverse	13 x 4 x 1 crescent cut perpendicular to axis of tube	Measurements on heating and cooling one cycle
5	CVD Tungsten	Longitudinal	44 x 4 x 2.5 rectangular bar cut parallel to axis of tube	Measurements on heating and cooling one cycle
6	CVD Tungsten	Transverse	28 x 5 x 2.5 crescent cut perpendicular to axis of tube	Measurements on heating and cooling one cycle
7	Norton Tungsten	Longitudinal	46 long 6 diameter rod	Measurements on heating and cooling cycle
8	Plansee Molybdenum	Transverse	42 x 5 x 2 rectangular bar cut parallel to axis of tube	Measurements on heating and cooling one cycle
9	W Graphite	Longitudinal	43 x 5 x 5 rectangular bar cut parallel to axis of tube	Measurements on heating and cooling one cycle
10	W Graphite	Transverse	22 x 5 x 2 crescent cut perpendicular to axis of tube	Measurements on heating and cooling two cycles

TABLE II

COEFFICIENT OF LINEAR EXPANSION OF TEN MATERIALS BETWEEN 20 and 1500°C

Temperature Interval °C	10^6 Linear Coefficient of Expansion, deg C^{-1}											
	#1		#2		#3		#4		#5		#6	
	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
20-100	4.5	4.6	3.5	3.1	3.6	3.8	3.8	3.9	5.9	5.7	-	-
100-200	3.3	3.6	3.4	3.1	3.8	3.9	4.0	4.0	5.7	5.2	7.1	6.9
200-300	4.1	4.1	3.9	3.1	4.4	3.9	4.4	4.4	5.2	5.0	6.5	5.9
300-400	4.3	4.6	4.4	3.6	4.3	3.9	4.1	4.1	5.6	5.0	6.7	5.9
400-500	4.6	4.7	6.1	4.0	4.7	3.9	5.1	5.1	5.5	5.0	5.8	5.4
500-600	5.2	4.7	6.1	4.7	4.5	4.0	4.0	4.0	5.7	5.0	5.6	5.3
600-700	5.1	4.7	8.0	4.8	4.7	4.6	4.9	4.9	5.4	5.2	5.4	5.2
700-800	5.0	4.8	4.6	4.8	4.8	4.6	4.4	4.6	4.8	4.8	5.2	5.2
800-900	4.8	4.8	4.6	4.8	4.6	4.6	4.8	4.6	4.8	4.8	5.0	5.0
900-1000	4.7	4.8	4.9	4.8	4.6	4.6	4.8	4.6	4.9	4.9	4.9	4.9
1000-1100	4.8	4.9	4.7	4.8	4.5	4.6	4.5	4.0	4.9	4.9	4.8	4.8
1100-1200	4.8	4.9	5.3	4.8	4.5	4.6	4.5	4.6	4.9	4.9	4.6	4.8
1200-1300	3.3	5.0	5.7	4.8	4.5	4.6	4.5	4.5	5.2	5.2	5.2	5.5
1300-1400	5.3	5.0	5.4	4.8	4.7	4.7	4.8	4.8	5.0	5.0	5.8	5.6
1400-1500	5.2	5.8	4.8	4.8	-	-	3.9	5.0	5.9	5.9	5.9	5.6
Initial length mm	47.75	-	48.55	1	20.70	-	12.6	-	44.59	-	22.96	-
Final length mm	-	47.75	-	48.58	-	20.70	-	12.6	-	44.59	-	22.96

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TABLE II (continued)

Temperature Interval °C	10^6 Linear Coefficient of Expansion, deg C^{-1}											
	#7		#8		#9				#10			
	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
20-100	5.8	5.0	6.3	6.2	2.2	-	-	2.2	7.7	-	7.4	5.2
100-200	5.8	4.8	6.7	6.2	2.4	2.4	2.4	2.4	7.0	5.7	7.1	5.2
200-300	5.6	4.4	6.7	6.3	2.8	2.4	2.5	2.2	7.3	4.9	7.7	4.8
300-400	5.5	4.5	6.7	6.1	3.3	2.2	2.6	2.3	7.7	4.6	8.0	5.2
400-500	5.4	4.6	6.6	6.2	2.8	2.3	2.8	2.3	8.0	4.7	8.1	5.4
500-600	5.3	4.6	6.5	6.2	2.9	2.3	2.9	2.4	7.7	5.0	7.5	5.6
600-700	5.2	4.7	6.7	6.2	3.0	2.7	3.0	2.7	6.3	5.5	6.5	5.8
700-800	5.2	4.8	6.7	6.7	3.0	2.7	3.2	2.8	6.3	6.6	6.4	5.9
800-900	5.2	5.0	6.7	6.6	3.0	2.7	2.3	2.7	6.2	6.5	6.3	6.1
900-1000	5.2	5.0	6.7	6.6	2.2	2.7	2.3	2.6	6.2	6.9	6.0	6.9
1000-1100	6.1	5.0	6.7	6.0	2.2	2.7	2.3	2.5	6.1	8.6	5.3	8.6
1100-1200	6.0	5.0	6.8	7.0	2.1	2.7	2.3	2.6	5.8	8.7	5.3	8.7
1200-1300	5.8	5.0	6.8	7.0	2.0	1.9	2.1	1.9	5.3	8.7	5.6	8.7
1300-1400	4.8	5.0	7.0	7.0	2.0	6.5	offscale		4.7	8.8	5.2	8.8
1400-1500	5.9	5.9	8.0	7.4	0	9.0	-		4.6	9.3	4.0	9.3
Original length mm	47.30		41.70		43.63		43.56		21.98		21.98	
Final length mm		47.25		41.70		43.56		43.46		21.98		21.95

TABLE III

TABLE OF $10^3 \frac{\Delta L}{L}$ FOR TEN SAMPLES TESTED

Sample	#1		#2		#3		#4	
Temperature °C	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
20-500°C	1.99	1.77	2.19	2.11	2.01	2.03	2.00	1.90
-700°C	3.03	2.71	3.62	3.06	2.93	2.82	2.88	2.85
-900°C	4.01	3.67	4.53	4.02	3.87	3.74	3.80	3.77
-1100°C	4.96	4.64	5.49	4.98	4.78	4.66	4.73	4.63
-1300°C	5.98	5.61	6.59	5.94	5.68	5.58	5.63	5.42
-1500°C	6.94	6.94	7.60	6.90	6.15*	6.05*	6.50	6.52
Remarks	Mixiumum Temperature 1520°C		Some Change Between 1500-1540°C		*At 1400°C Trouble Developed at 1420°C		Maximum Temperature 1517°C	

Sample	#5		#6		#7		#8	
Temperature °C	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
20-500	2.55	2.59	2.91	2.98	2.52	2.60	3.18	3.26
-700	3.66	3.59	4.02	4.03	3.58	3.53	4.59	4.50
-900	4.63	4.56	5.15	5.05	4.62	4.51	5.82	5.83
-1100	5.60	5.55	6.12	6.02	5.75	5.51	7.16	7.09
-1300	6.59	6.57	7.00	7.05	6.93	6.51	8.43	8.49
1500	7.70	7.70	8.17	8.17	8.10	7.60	9.93	9.93
Remarks	Maximum Temperature 1520 °C		Maximum Temperature 1515°C		Small Shrinkage Above 1520 °C		Small Shrinkage Above 1500 °C	

TABLE III (Continued)

Sample Temperature °C	1 Heating	Cooling	2 Heating	Cooling	1 Heating	Cooling	2 Heating	Cooling
20-500	1.43	-0.97	1.22	0.78	3.66	1.95	3.68	2.15
-700	2.11	-0.47	1.79	1.29	4.77	2.93	5.06	3.28
-900	2.81	-0.08	2.36	1.84	6.09	4.24	6.32	4.47
-1100	3.23	0.62	2.83	2.35	7.21	5.78	7.44	6.04
-1300	3.66	1.12	3.30	2.80	8.36	7.53	8.53	7.77
-1500	3.85	2.69			9.29	9.29	9.45	9.45
Remarks	Large Shrinkage Above 1515°C		Off Scale Above 1320°C		Max. Temperature 1510°C		Max. Temperature 1505°C	

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All data referenced to initial zero of measuring system.

TABLE IV

CVD SILICON CARBIDE BEND TESTS

Sample No.	A	B	C	D	E	W (C+D)/2	t (A+B)/2	a	F LB	Maximum Tensile Stress, psi
1	.029	.030	.3735	.372	7/8	.373	.0295	.730	28.000	94,400
2	.0305	.031	.374	.375	7/8	.3745	.0308	.730	15.500	47,800
3	.031	.032	.377	.377	13/16	.377	.0315	.730	42.300	123,870
4	.031	.030	.377	.377	13/16	.377	.0305	.730	43.900	137,180
5	.0305	.0305	.374	.3745	27/32	.3742	.0305	.730	36.600	115,260
6	.036	.0375	.370	.371	7/8	.3705	.0368	.730	37.800	82,400
7	.0335	.034	.376	.3755	27/32	.3758	.0338	.730	36.000	91,844
8	.016	.016	.3745	.3745	13/16*	.3745	.0160	.730	08.300	94,670
9	.0325	.0315	.371	.372	13/16	.3715	.0320	.730	31.500	90,570
10	.0375	.039	.372	.372	7/8	.372	.0382	.730	52.500	105,900
11	.024	.2045	.353	.353	7/8*	.353	.0242	.730	21.500	113,950
12	.026	.028	.351	.351	7/8	.351	.0270	.730	12.900	55,260
13	.022	.022	.362	.3625	7/8	.3622	.0220	.730	14.800	92,550
14	.011	.0115	.357	.357	7/8	.357	.0112	.730	3.810	93,520

FORMULA:

$$\text{STRESS} = \frac{(1.5)\ (F)\ (.730)}{(W)\ (t^2)}$$

TABLE V

SiC RINGS - DEPOSITING AND ANNEALING EFFECTS ON MECHANICAL PROPERTIES

Specimen	Condition	Diam. (in.)	Wide (b,in.)	Thick (h,in.)	Radius (r, in.)	Maximum Load (P,lb.)	Comp. Stress PSI	Tens. Stress PSI
C-69-9-8, #3	Unannealed	-.005	.404	.030	.523	7.8	68,000	67,000
C-69-9-8, #4	Annealed	0	.393	.030	.521	9.9	88,200	86,600
C-69-9-15, #1	Annealed	0	.400	.035	.531	8.0	52,500	51,400
C-69-9-15, #2	Annealed	0	.381	.044	.529	8.2	35,700	34,700
C-69-9-17	Annealed	0	.382	.033	.452	3.5	23,000	22,400
C-69-6-18 #1	Annealed	0	.380	.058	.560	24	64,100	62,900
C-69-9-21, #1	Annealed	0	.376	.037	.541	8.1	51,700	50,500
C-69-9-21, #2	Unannealed	0	.360	.040	.538	8.4	47,600	46,400
C-69-9-22, #1	Annealed	0	.387	.040	.542	10.9	57,900	56,500
C-69-9-22, #2	Unannealed	0	.372	.041	.542	8.5	44,700	43,500
C-69-9-23, #2	Unannealed	-.005	.344	.046	.545	14.3	65,100	63,300

FORMULA:

$$\text{STRESS} = \frac{P}{bh} \pm \frac{6Pr}{bh^2}$$

TABLE VI

DIODE TESTS

Diode Test	Test Date Start	Stop	Protective Envelope	Test Hours	Watts Output	Location of Failure	Commentary
499	8-19-68	8-20-68	Integral Silicon Carbide	2	20		
500	9-7-68	10-16-68	Free-Standing	106	105	Free-Standing Shell, Open End	
501	11-11-68	11-19-68	Integral and Free-Standing Silicon Carbide	34	NT	Integral Shell, Total Length	
502	12-9-68	12-11-68	Iridium and Integral Silicon Carbide	21	84	Integral Shell Open End	
503	12-19-68	12-29-68	Integral Silicon Carbide and Silicon	128	80	Integral Shell, 2" from closed end	
504	2-20-69	2-24-69	Integral Silicon Carbide	12	66	Integral Shell, Closed End	
505	5-7-69	5-12-69	Integral Silicon Carbide	18	NT	Integral Shell, Spalled at Open End	Tungsten -5% Molybdenum Emitter
506	6-18-69	6-19-69	Integral Silicon Carbide	12	63	No Failure; Diode on Standby	Sintered Tungsten Emitter

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TABLE VI (Continued)

Diode Test	Test Date Start	Test Date Stop	Protective Envelope	Test Hours	Watts Output	Location of Failure	Commentary
507	6-18-69	6-19-69	Integral Silicon Carbide	3	NT	Collector, near Weld	Cup & Glass Joint Protection
508	7-2-69	7-30-69	Integral Silicon Carbide	406	78	Integral Shell, Hot Zone	Cup & Glass Joint Protection
509	8-20-69	9-10-69	Integral Silicon Carbide	385	67	Integral Shell, Hot Zone	Cup & Glass Joint Protection
510	9-8-69	9-19-69	Integral Silicon Carbide	60	60	No Failure; Diode on Standby	Cup & Glass Joint Protection

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